# CURVATURE-SIZE RELATIONSHIPS OF PORT CAMPBELL AUSTRALITES, VICTORIA

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## Abstract

Statistical studies, utilizing frequency polygons and scatter diagrams, of the relationships between size of well-preserved australites from Port Campbell, Victoria, and radii of curvature of their posterior and anterior surfaces, result in the conclusion that they represent secondary modifications of a few primary forms of extraterrestrial glass. Primary shapes consisted principally of spheres, which did not rotate, and a proportion of spheroids, dumb-bells and apioids which are fundamentally forms of revolution. The secondary shapes possessed by australites were formed from these few primary shapes which entered the earth's atmosphere as non-rotating, cold bodies. Buttons, lenses and round cores arose from primary spheres. Ovals, boats, canoes, dumb-bells, teardrops and elongated cores developed from primary spheroids, dumb-bells and apioids. The secondary shapes were sculptured in the earth's atmosphere by processes of ablation, thin-film fusion-stripping and skin friction operating upon forward surfaces at ultra-supersonic speeds of earthward flight.

## Part I—Round Forms

### Introduction

Among nearly 1,500 australites discovered during the past twenty years in the Port Campbell district of south-western Victoria, 571 complete or nearly complete forms are well preserved and suited to the accurate determination of depth and diameter and of arcs and radii of curvature of their anterior and posterior surfaces respectively. For the purposes of curvature-size relationships, the Port Campbell australites have been treated in two principal groups—(i) Round Forms, and (ii) Elongated Forms. The percentages of the various round forms of australites dealt with in Part I of this study are shown in Table 1.

Table 1

| Group | Shape Type | Numbers of Specimens | Percentage of total number of the forms measured |
|---|---|---|---|
| ROUND FORMS | Buttons | 295 | 51·7 |
| | Hollow buttons | 4 | 0·7 |
| | Round discs and round plates | 15 | 2·5 |
| | Round bowls | 5 | 0·9 |
| | Lenses | 64 | 11·2 |
| | Round cores | 22 | 3·9 |
| | | | 70·9% |
| ELONGATED FORMS | Ovals, boats, teardrops, dumb-bells, etc. | 166 | 29·1% |

The shape terminology is based upon Fenner's (1940, p. 312) classification of australites.

This paper (Part I) is concerned with (i) the Round Forms of australites, of which there are 405 well-preserved specimens, constituting nearly 71% of the total

of all forms suited to accurate measurement. The term "Round Forms" is applied here to those australites that possess a circular outline in plan, i.e., when viewed along the polar directions the equatorial outline is circular.

The several types of the round forms of australites are:

(a) Buttons—with flanges.
(b) Hollow buttons—with internal cavities.
(c) Lenses—with rim but no flange.
(d) Round cores—with flaked equatorial zones and never flanged.
(e) Round discs and round plates—flat, thin forms.
(f) Round bowls—posterior and anterior surfaces curved in the same sense, never flanged.

There are statistically sufficient numbers of specimens for significance in each of types (a), (c) and (d). By virtue of their excellent state of preservation, the Port Campbell australites lend themselves especially well to a detailed study of the curvature of their two surfaces—(1) the primary posterior surface and (2) the secondarily developed anterior surface. The radii of curvature determined for these two surfaces on over 400 round forms of the Port Campbell australites are herein compared with one another and with the measured values of depth and diameter and of the intercepts of the diameter line upon the depth line (*cf.* Fig. 3). The comparisons are made by means of frequency polygons and scatter diagrams. All the values of the various measurements are given in millimetres.

Abbreviations used in the text are as follows:

$R_F$—radius of curvature of anterior surface.
$R_B$—radius of curvature of posterior surface.
De—true depth( or thickness) as measured between the front and back poles of the anterior and posterior surfaces respectively (*cf.* Fig. 3).
Di—true diameter (the radical line), as measured by construction, between the points of intersection of two coaxal circles, portions of which represent the arcs of curvature of anterior and posterior surfaces respectively (*cf.* Fig. 3).
OM—distance from front pole (M—on anterior surface) to centre of radical line (diameter).
ON—distance from back pole (N—on posterior surface) to centre of radical line (diameter).

OM and ON represent the intercepts on the depth line (MN) cut off by the radical line (KL) as indicated in Fig. 3, and their summation is thus equal to the true depth, so that OM + ON = MN = De.

## Curvature of Surfaces

Sketch diagrams of the types of round forms measured are shown in Fig. 1.

In Fig. 1, the sketches of the normal flanged button, the small flanged button, the lens and the round core are depicted in three-dimensional aspects. Horizontal planes (diagonal shading) are circular; vertical planes (solid black) have the same outlines as those drawn in the plane of the paper. Sectional outlines of flanges are shown in the equatorial regions of the normal and small flanged buttons, but in order that the core (or body) portions of the buttons could be compared and contrasted with the lens type, flanges have been omitted from both diameter measurements and from radii and arc of curvature considerations. Measurements of the curvature of the surfaces of round bowls and of round discs (or round plates)

ROUND FORMS OF AUSTRALITES



NORMAL FLANGED
BUTTON

ROUND BOWL

LENS

SMALL FLANGED
BUTTON

ROUND DISC (OR PLATE)
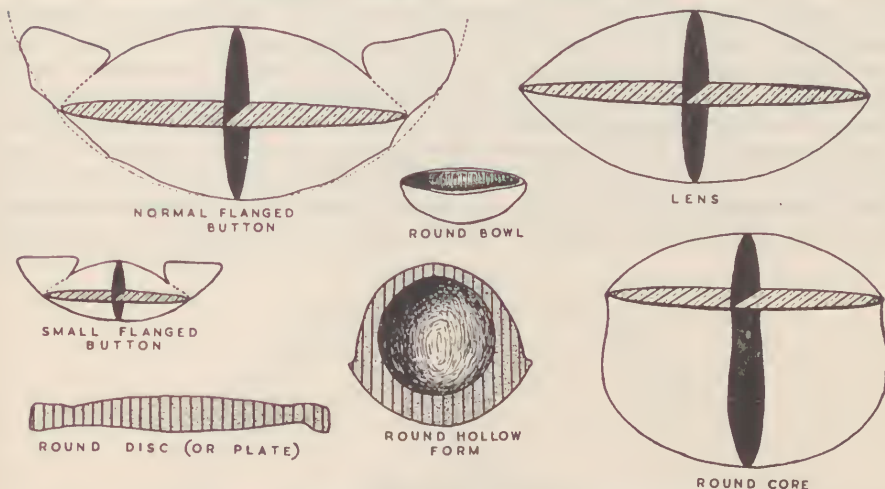
ROUND HOLLOW
FORM

ROUND CORE

Fig. 1.—Sketch diagrams of round forms of Port Campbell australites. In each sketch the posterior surface of the form is at the top. All enlarged 2·75 times except the round hollow form, which is 0·5 times.

had little statistical significance, in view of the small populations among these types.

## Method of Obtaining Arcs and Radii of Curvature

Each suitably preserved australite was placed in the focus of a horizontal beam of light and its silhouette traced at 5·5 magnifications. On the outlines so produced, three chords were drawn for each of the two surfaces (anterior and posterior surfaces respectively), and each chord was bisected as indicated in Fig. 2. Normals to the chords through the points of bisection, mostly met at three-point intersections, as in Fig. 2; a few met to produce a small triangle of error. With the points of intersection of the bisectrices as foci (Y and Z in Fig. 2), circles were constructed about the curved anterior and posterior surfaces, and in most examples showed almost perfect coincidence with the curvature of these surfaces. Minor irregularities caused by the presence of bubble pits on posterior surfaces and flow ridges on anterior surfaces were smoothed out in the silhouette tracings. Each australite was rotated in the beam of light through 45° and 90° about the polar axis, and in each position the arc of curvature of each surface matched the original silhouette tracing, indicating the maintenance of similar curvature all over the anterior surface, and similar curvature all over the posterior surface.

The relationships of the curvature of anterior and posterior surfaces respectively vary somewhat from form to form according as to whether the back or front pole is situated nearer to the centre of the radical line (= diameter line). A characteristic relationship is indicated in Fig. 3.

In Fig. 3, NM is the depth line joining the back pole on the posterior surface and the front pole on the anterior surface. KL is the radical line which joins the points of intersection of the two coaxal circles circumscribed one about the posterior surface and the other about the anterior surface. One of these circles

passes through the back pole (N) and the other passes through the front pole (M). These circles, constructed about each arc of curvature obtained in the silhouette tracings, were shown to be coaxal by virtue of the depth line NM being normal to the radical line, and the foci (Y and Z) of the arcs of curvature were thus collinear, being located on the depth line or its extension beyond the limits of the outline of each form as determined by the construction shown in Fig. 2. The arc of curvature KML in Fig. 3 provides the radius of curvature ($zM = R_F$) of the secondarily developed anterior surface in australites, while KNL provides the radius of curvature ($yN = R_B$) of the remnant portion of the primary posterior surface. The lines KL and NM in the construction (Fig. 3) provide measures of
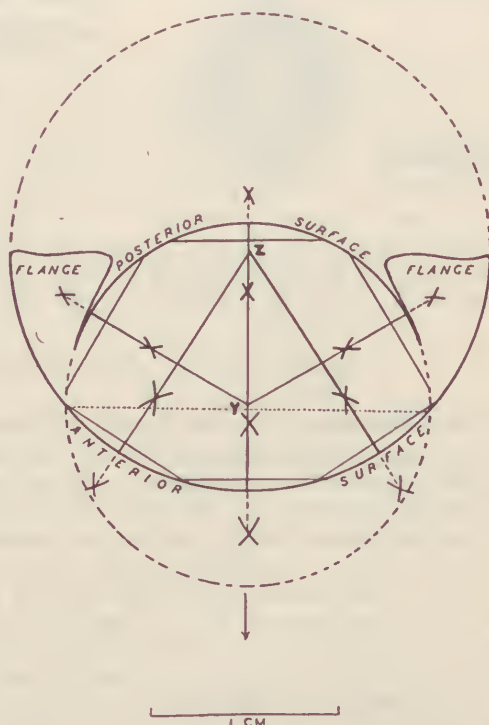


Fig. 2.—Actual trace of silhouette of button-shaped Port Campbell australite, illustrating method of determining radii of curvature, depth and diameter of a form having $R_F = 12.5$ mm., $R_B = 9.5$ mm., De = 14.0 mm., Di (ex-flange) = 19.0 mm., OM = 4.0 mm., and ON = 10.0 mm. (All measurements taken to the nearest 0.5 mm.)

the true diameter and true depth for an australite, when the measured values are reduced according to the reduction factor appertaining to the particular enlargement of the silhouette tracing. The intercept ON of the radical line upon the depth line (Fig. 3) provides a measure of the distance of the back pole (N) from the centre (O) of the radical line (KL), while the OM intercept provides a measure of the distance away of the front pole (M). Since the radical line is contained in a circular plane and (O) is the mid-point in this plane, it follows that the

intercepts ON and OM represent the distances of back and front poles respectively from the centre of the circular horizontal plane. It will be shown later that this plane is not always a plane of symmetry, hence (O), the mid-point of the horizontal plane, does not coincide with the centre of the australite, unless ON and OM have the same values. It will be seen from the following frequency polygons and scatter diagrams depicting ON and OM values, and the ratios between these values, that the distances between the back and front poles and the centre (O) of the circular horizontal plane containing KL vary a little from group to group and sometimes from form to form in the same group, but a large number of forms have ON and OM equal in amount. Hence the point (O) is frequently the central point of the australite.
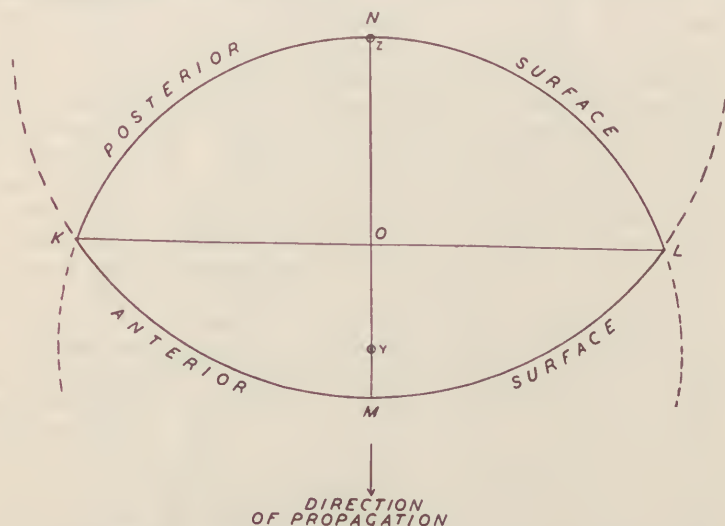


FIG. 3.—Sketch showing relationship of curvature of anterior and posterior surfaces of a typical round form of the Port Campbell australites.

## Standardization of Measurements and Comparisons

As indicated above, measurements of the secondary flange structure in the equatorial regions of flanged australites have been purposely omitted from $R_F$ and Di considerations. There are two main reasons for this procedure. The first is that all flanges do not possess the same arc of curvature as the body portions to which they are attached. One and the same arc of curvature is indicated for the anterior surface of flange and body alike in Fig. 2, but such examples are not universal, as there exist several button-shaped forms in which the anterior surface of the flange tends to be flatter and several where it is steeper than that of the body portion. A second reason is that in comparisons between flanged buttons and the non-flanged lenses and the non-flanged round cores, the flange structures of the buttons have to be omitted from consideration, otherwise errors in diameter relationships would arise. For example, the inclusion of the flange width in overall diameter measurements of a flanged button could provide a greater value than for a non-flanged lens, and yet the diameter of the lens might be greater than that of the comparable body portion of the flanged button. It is thus important to

standardize this factor for the purposes of radii of curvature and diameter deter-
minations. Since it is impossible, by virtue of their very nature, to directly measure
the diameters of the body portions of buttons possessing complete or nearly com-
plete attached flanges (unless resort is made to needlessly destroying such complete
forms by fracturing away the flange), diameter measurements of the body portions
were obtained from the silhouette tracings by construction (*cf*. Figs. 2 and 3).
Such measurements are accurate to the nearest 0·5 mm.

The significance of excluding the flange structures from comparative studies
involving diameter and radii of curvature measurements can be gained from the
following remarks. In many large collections of australites that have been described
and classified there is often a marked preponderance of lens-shaped forms over
button-shaped forms. There is little doubt that this state of affairs arises from
the much-abraded condition of most specimens in such collections. On the other
hand, the australites found in the Port Campbell district come from a region where
abrasion processes have been at a minimum, and moreover, only the best-preserved
specimens have been utilized in curvature-size studies. Hence button-shaped aus-
tralites are more numerous than lens-shaped australites. The original parentage of
many broken, etched and partially abraded round forms of australites can often be
detected by searching their surfaces for traces of remnant structures such as minute
flange remnants, or the occurrence of the smooth annular areas known as "flange
bands" which are sometimes preserved in the equatorial regions of posterior
surfaces and mark the sites of attachment of pre-existing flanges. Such remnants
point to an original button parentage among the round forms of australites, and
hence such specimens can be safely utilized for diameter and radii of curvature
measurements in the button-shaped types of australites. The complete removal of
vestiges of flange structures by excessive weathering would lead to classification
with the non-flanged lens group, resulting in an undue weighting of numbers
among the lens type australite population. This in itself, however, may not be a
serious factor in the curvature-size relationships as between buttons and lenses,
since it is shown in the following frequency polygons and scatter diagrams that
there is a close similarity between the body portions of button-shaped australites
and the lens-shaped australites. It does, however, explain why collections composed
of well-preserved specimens contain a higher proportion of buttons with flanges,
while collections composed of strongly abraded specimens contain a higher propor-
tion of the non-flanged lenses. This factor would become important in comparing
curvature-size relationships for round forms from different districts.

Among the Port Campbell australites selected for curvature-size studies, every
precaution has been taken to prevent over-weighting of numbers in any particular
shape type that might arise from the wrong classification of somewhat abraded
forms. This aim has been greatly aided by the excellent state of preservation of
most specimens in the collection, and the omission of all of doubtful classification.
Round forms with flanges are thus definitely button-shaped types. Round forms
resembling the body portions of buttons, possessing rims only and no traces what-
soever of flange remnants, are classified as lenses, developed as such by a process
of atmospheric flight-shaping, wherein all traces of flange, if ever developed, had
already been removed by ablation and fusion-stripping during high-speed traverse
through the earth's atmosphere.

It has been found from the constructions typified by Figs. 2 and 3 that of the
two respective coaxal circles circumscribed about the arcs of curvature of the
anterior and posterior surfaces, one coaxal circle fits around the front polar regions

TABLE 2

*Ranges in Curvature-Size Measurements of 405 Round Forms of the Port Campbell Australites*

| Shape Type | Percent of Round Forms | $R_F$ (mm.) | $R_B$ (mm.) | Ratio $R_B : R_F$ | Diameter(mm.) (Di) | Depth(mm.) (De) | Ratio De : Di | Intercept OM (mm.) | Intercept ON (mm.) | Ratio OM : ON |
|---|---|---|---|---|---|---|---|---|---|---|
| Buttons .. | 73·0 | 5·0–18·5 | 2·0–24·5 | 1 : 0·36–<br>1 : 4·00 | 2·5–33·0 | 2·5–19·5 | 1 : 0·56–<br>1 : 3·30 | 0·5–12·5 | 1·0–10·0 | 1 : 0·10–<br>1 : 5·00 |
| Hollow Buttons .. | 1·0 | 12·0–18·5 | 10·0–17·5 | 1 : 0·91–<br>1 : 1·60 | 17·5–30·0 | 16·0–28·0 | 1 : 0·93–<br>1 : 1·50 | 2·5–23·0 | 7·0–20·0 | 1 : 0·30–<br>1 : 6·00 |
| Round discs and Round Plates | 3·5 | 5·0–28·0 | 3·5 → | 1 : 1–<br>1 : 4·13 | 6·5–14·0 | 1·0–2·5 | 1 : 2·80–<br>1 : 7·00 | 0·25–1·0 | 0·75–2·0 | 1 : 1–<br>1 : 4 |
| Round bowls | 1·0 | 4·5–9·0 | 49·0 → | — | 9·0–16·5 | 1·0–4·5 | 1 : 2·00–<br>1 : 9·50 | — | — | — |
| Lenses .. | 16·0 | 5·5–13·0 | 4·5–17·5 | 1 : 0·40–<br>1 : 1·90 | 8·0–19·0 | 3·5–12·5 | 1 : 1·50–<br>1 : 2·90 | 1·0–4·5 | 1·0–8·0 | 1 : 0·35–<br>1 : 2·50 |
| Round Cores | 5·5 | 8·0–20·5 | 11·0–36·0 | 1 : 0·42–<br>1 : 1·20 | 14·5–34·0 | 10·5–24·5 | 1 : 1·20–<br>1 : 2·30 | 5·0–13·5 | 2·5–14·5 | 1 : 0·22–<br>1 : 1·45 |

→ ≡ ∞, and as in round bowls, curvature is in a negative sense.

and across the tops of the flow ridges nearest the polar regions on the anterior surface (*cf.* sketch of normal flanged button in Fig. 1). The other coaxal circle fits across the tops of the walls of surface bubble pits exposed on the posterior surface. All the arcs of curvature constructed about the anterior and posterior surfaces of the 405 round forms studied were standardized on this basis.

On flanged forms of australites it can be observed (*cf.* Fig. 2) that the posterior coaxal circle intersects the anterior coaxal circle in the region of the line of union between flange and body portions; moreover, the arc of curvature of the line of union between these two structures is identical in degree and position with that of the constructed posterior coaxal circle.

The true diameters of round cores (sometimes called "bungs"), such as the specimen depicted in sketch form in Fig. 1, which possesses a flaked equatorial zone (recessed region below horizontal plane in sketch), were all measured from graphical constructions based on silhouette tracings. The distance between the points of intersection of coaxal circles described around anterior and posterior surfaces respectively was taken as the true diameter of each round core form prior to the development of the flaked equatorial zone by fusion-stripping during rapid non-rotational flight through the earth's atmosphere. These points of intersection thus lie outside the silhouette tracings of such forms.

### Radii of Curvature, Depth, Diameter and Intercept (OM and ON) Values

The measured values of the radii of curvature of anterior and posterior surfaces, of depths and of diameters for the round forms of australites from the Port Campbell district are summarized in Tables 2 and 3, according to the various shape types represented. Ranges in these values are listed in Table 2; average values have been calculated and are listed in Table 3. The calculated average values are compared in Table 4 with the model values obtained from the construction of frequency polygons.

Tables 2 to 4 show the general trends in the variations of $R_F$, $R_B$, Di, De, OM and ON from shape type to shape type among round forms of australites from the Port Campbell district. There are marked increases in the values of all the measurements from round discs and plates, through lenses and buttons to round cores and hollow buttons. Ranges and average values for the several curvature and size measurements among the button type of australite include both the normal and the small flanged buttons. With increased radii of curvature and hence flattening of the arc of curvature of their surfaces, the smaller of the small flanged buttons merge into the shape type composed of the round discs and plates.

Radius of curvature values for the posterior surfaces ($R_B$ in Tables 2 and 3) of the round discs and round bowls range up to infinity as certain forms attain virtual flatness of this surface. The radius of curvature values of the posterior surface ($R_B$) of some round bowls include a few specimens in which the arcs of curvature of the posterior surfaces are directed in the same sense as that of their anterior surfaces. Such forms, which are thin (approximately 1 mm.) have passed beyond the flattened condition and have become bent backwards while softened.

The ratios between the pairs of measurements (a) $R_F$ and $R_B$, (b) Di and De, and (c) OM and ON, are listed in Tables 2, 3 and 4. In these pairs of measurements, $R_B$, De and OM were retained at unity in calculating the ratios. Comparisons of these ratios from shape type to shape type reveal certain similarities and a few marked variations. Thus the calculated average ratio of $R_B$ to $R_F$ is very

TABLE 3

*Average Values of Curvature-Size Measurements of 405 Round Forms of the Port Campbell Australites.*

| Shape Type | Percent of Round Forms | $R_F$ (mm.) | $R_B$ (mm.) | Ratio $R_B : R_F$ | Diameter (mm.) (Di) | Depth (mm.) (De) | Ratio De : Di | Intercept OM (mm.) | Intercept ON (mm.) | Ratio OM : ON |
|---|---|---|---|---|---|---|---|---|---|---|
| Buttons .. | 73·0 | 9·5 | 8·5 | 1 : 1·20 | 14·0 | 7·5 | 1 : 1·91 | 3·5 | 4·5 | 1 : 1·42 |
| Hollow Buttons .. | 1·0 | 15·5 | 13·5 | 1 : 1·20 | 24·0 | 22·0 | 1 : 1 | 10·0 | 12·0 | 1 : 2·8 |
| Round discs and Round Plates | 3·5 | 12·0 | 8·0 | 1 : 2·20 | 9·5 | 2·0 | 1 : 5 | 0·5 | 1·5 | 1 : 2·7 |
| Round bowls | 1·0 | 6·5 | — | 1 : 0·13 (1 sp.) | 11·0 | 3·0 | 1 : 5 | 2·5 (1 sp.) | 0·5 (1 sp.) | 1 : 0·2 (1 sp.) |
| Lenses .. | 16·0 | 8·5 | 8·0 | 1 : 1·12 | 12·0 | 6·0 | 1 : 2·1 | 3·0 | 3·0 | 1 : 1·2 |
| Round Cores | 5·5 | 14·0 | 17·0 | 1 : 0·86 | 24·5 | 15·5 | 1 : 1·7 | 9·0 | 6·0 | 1 : 0·7 |

similar in buttons, hollow buttons and lenses, but markedly higher in the round discs, lower among the round cores and round bowls. The ratio of De to Di shows significant variations from type to type among the various shapes, while the ratio of the intercepts OM to ON shows marked differences from shape type to shape type. However, when these ratios are compared in terms of the modes of the frequency polygons (Table 4), minor variations are smoothed out between the more densely populated shape types of the buttons, lenses and cores. This is because the frequency polygons are based upon measurements taken to the nearest $0 \cdot 5$ mm., whereas the calculated average values of the ratios are based on determinations taken to the nearest $0 \cdot 1$ mm. (as obtained by applying the reduction factor in connection with measurements derived from the silhouette constructions).

Table 4 reveals unit ratio for $R_B : R_F$ relationships, a two to one ratio for Di : De relationships, and significant variations from shape to shape for OM : ON relationships. The variations in OM : ON relationships signify that in button-shaped australites the front pole is more usually a little nearer to the centre of the horizontal plane than is the back pole, while lenses are more consistently lenticular, bilaterally symmetrical objects, with front and back poles approximately equally spaced on either side of the centre of such forms, the centre thus being contained in a horizontal plane of symmetry. In round cores, on the other hand, the front pole is usually spaced twice as remote from the centre of the horizontal plane than is the back pole, and the horizontal plane is not a plane of symmetry.

These variations in OM : ON relationships, reflecting as they do variations in the spacing of back and front poles from the centre of the horizontal plane, can be explained in terms of varying degrees of reduction of original primary spheres, or spheroids approximating to spheres, of different original sizes. Reduction resulted from ablation and fusion stripping to different degrees during rapid earthward, non-rotary transit through the atmosphere. Many of the secondary resultant round cores indicate least reduction of the primary form on this basis, while secondary resultant flanged buttons and lenses indicate far greater amounts of ablation of the original primary forms.

### Frequency Polygons and Scatter Diagrams

In the following frequency polygons depicting the relationships of the various measurements to the numbers of forms in each particular shape type having the same values of these measurements, only the button, lens and round core types can be satisfactorily illustrated, for in each of these three shape types among the round forms of Port Campbell australites there are sufficient numbers of specimens to be statistically significant.

In the scatter diagrams, a particular measurement for each individual form studied in the button, lens and round core types has been plotted against each of the other selected measurements in turn. Because of their closely related values throughout, button-shaped and lens-shaped types have been grouped together for $R_B$-$R_F$, for De-Di, for ON-OM, for $R_B$-De, for $R_B$-Di, for $R_F$-De and for $R_F$-Di comparisons.

In Fig. 4 particular values of $R_B$, taken to the nearest $1 \cdot 0$ mm., are plotted against numbers of forms possessing the same $R_B$ value for the three main types of the round forms of australites. The greatest numbers of buttons and lenses have an $R_B$ value of 8 mm., while cores have a value double this amount. For $R_F$ values, however, although the values of the mode remain the same for lenses (8 mm.), the value for buttons is increased by 25% to 10 mm., while that for the round cores has decreased $12 \cdot 5$% to 14 mm. (see Fig. 5).

TABLE 4

*Modes of Frequency Polygons compared with Calculated Average Values of Curvature and Size Measurements of 385 Round Forms of Port Campbell Australites*

| Shape Type | | $R_F$ (mm.) | $R_B$ (mm.) | Ratio $R_B : R_F$ | Diameter (mm.) (Di) | Depth (mm.) (De) | Ratio De : Di | Intercept OM (mm.) | Intercept ON (mm.) | Ratio OM : ON |
|---|---|---|---|---|---|---|---|---|---|---|
| Buttons .. | Mode of Frequency Polygon | 10 | 8 | 1 : 1 | 14 | 8 | 1 : 2 | 3 | 4 | 1 : 1·5 |
| | Calculated Average Value .. | 9·5 | 8·5 | 1 : 1·2 | 14 | 7·5 | 1 : 1·9 | 3·5 | 4·5 | 1 : 1·4 |
| Lenses .. | Mode of Frequency Polygon | 8 | 8 | 1 : 1 | 12 | 6 | 1 : 2 | 3 | 3 | 1 : 1 |
| | Calculated Average Value .. | 8·5 | 8 | 1 : 0·9 | 12 | 6 | 1 : 2·1 | 3 | 3 | 1 : 1·2 |
| Round Cores | Mode of Frequency Polygon | 14 | 16 | 1 : 1 | 26 | 14 | 1 : 2 | 9 | 6 | 1 : 0·5 |
| | Calculated Average Value .. | 14 | 17 | 1 : 0·9 | 26 | 15·5 | 1 : 1·7 | 9 | 6 | 1 : 0·7 |
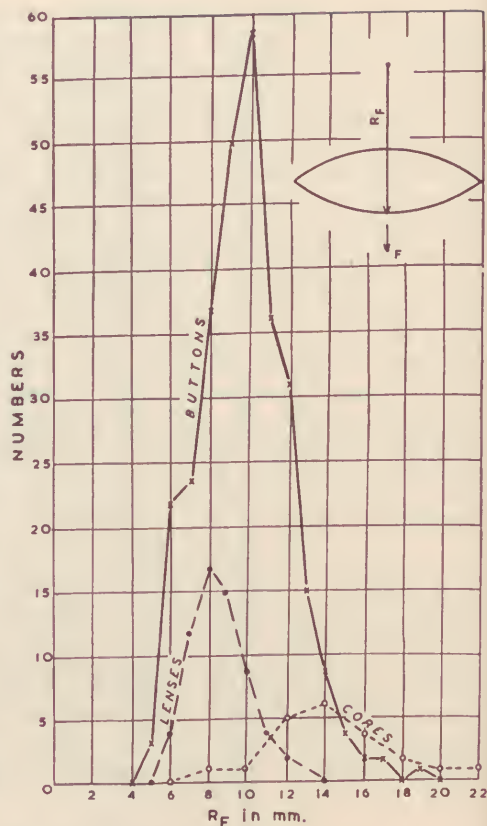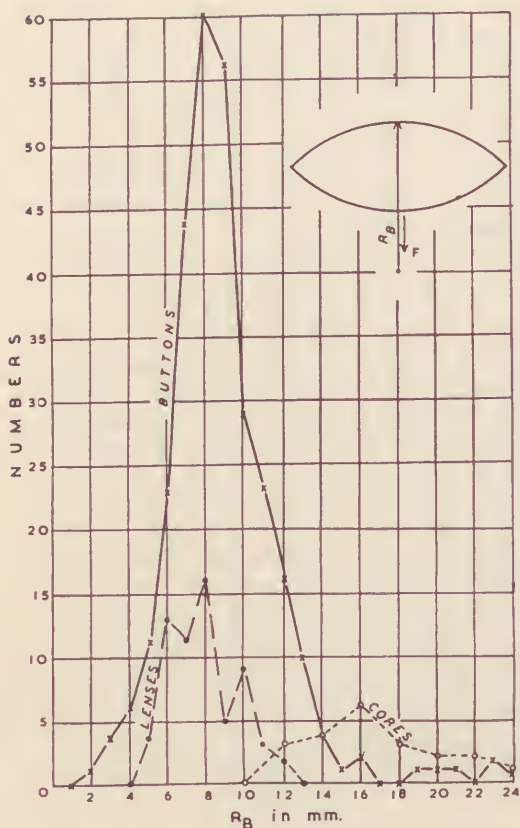
Figs. 4 and 5.—Frequency polygons showing $R_B$-Numbers and $R_F$-Numbers relationships for round forms of the Port Campbell australites.

*(The arrow and the letter F in this and other frequency polygons herein indicate the front surface and the direction of propagation of the australites through the earth's atmosphere.)*

In Fig. 6, depicting the relationships of the ratio $R_B : R_F$ and the numbers of round forms that possess similar values of this ratio, it is found that by using ratios determined to the nearest 0·5, nearly symmetrical polygons result for all three of the major shape types, each having a modal value at unit ratio. The polygons show (Fig. 6) that the greater numbers of the round forms of australites possess $R_F$ values which are approximately equal to their $R_B$ values, and that there is a significant proportion (37%) in which $R_F$ is 1·5 times as great as $R_B$.

The relationships between individual $R_B$ and $R_F$ values for the round forms of Port Campbell australites are shown in Fig. 7, which reveals a general tendency for $R_F$ values to increase with increase in $R_B$ values. This is not a steady increase, however, inasmuch as there are, for example, 30 specimens with the same $R_F$ value of 8 mm. and among these specimens there is a range in the $R_B$ values of from 2 to 12 mm. In other words, a number of primary forms with original diameters

ranging from 4 mm. to 24 mm. have all been ablated different amounts to produce ultimate secondary anterior surfaces having the same radius of curvature. These forms, however, do not all have the same depth values nor the same diameter values, hence the arcs of curvature of their posterior and anterior surfaces respectively show different dispositions in relation to their radical lines, so that the centres of the two coaxal circles are variously spaced from the radical lines in the different specimens.
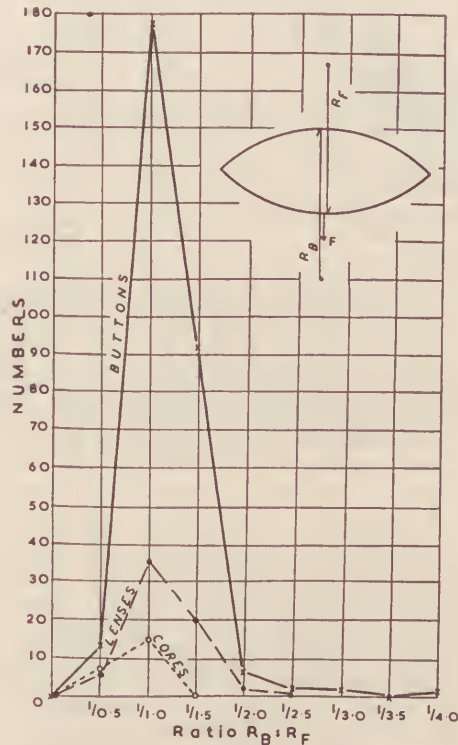


FIG. 6.—Frequency polygon depicting Ratio $R_B : R_F$-Numbers relationships for the round forms of Port Campbell australites.

Conversely, Fig. 7 reveals that there are, for example, about 40 specimens with approximately the same $R_B$ of 8 mm., but these show a range in $R_F$ values of from 5·5 mm. to 12 mm. In other words, 40 of the primary forms possessed a similar diameter of 16 mm., but by differential ablation, their ultimate secondarily formed anterior surfaces have different arcs and different radii of curvature, and hence different depths and different diameters.

Similar such variations as those outlined above occur for other values of both $R_F$ and $R_B$. Despite these variations, the total scatter for all the round forms included in the comparisons nevertheless reveal the general trend of increasing $R_F$ with increase in $R_B$; that is to say that with flatter arcs of curvature of posterior surfaces, which are usually encountered on the larger primary forms, the flatter arcs of curvature of secondarily produced anterior surfaces develop.
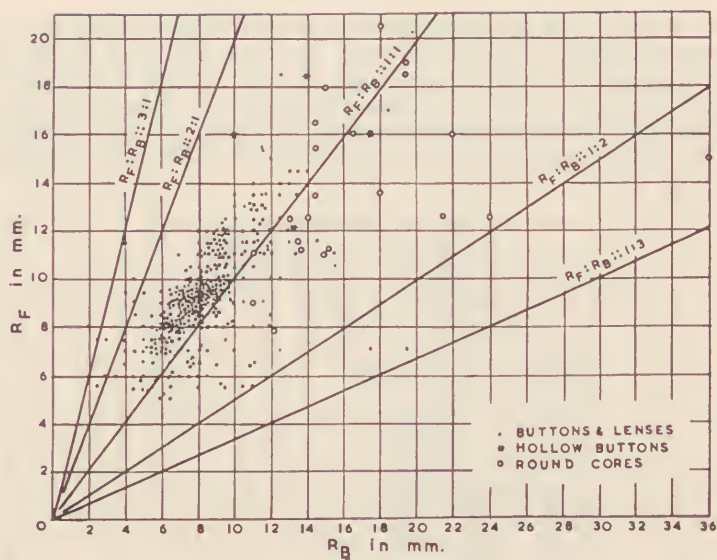
B

Fig. 7.—Scatter diagram illustrating $R_F$-$R_B$ relationships for each individual round form of the Port Campbell australites. (Round discs and round bowls excluded because of low numbers in each shape type, anomalous curvatures in round bowls and usually flat surfaces in round discs.)
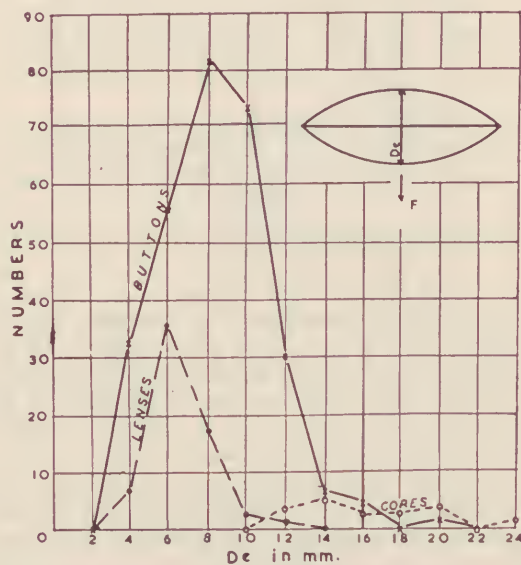


Fig. 8.—Frequency polygon showing Depth-Numbers relationships for round forms of the Port Campbell australites.

Fig. 7 shows a marked concentration of $R_F$-$R_B$ values for buttons and lenses between the unit gradient line and the 2 : 1 gradient line. $R_F$-$R_B$ values for the round cores show a considerable scatter.

The depth values of the round forms of australites from the Port Campbell district are shown in Fig. 8, where it can be observed that lenses, with depth values of 6 mm., are not as thick as buttons, in which the modal value is 8 mm., although significant numbers have depth values of 10 mm. The round cores are even thicker, but the distribution of their depth values is somewhat irregular, possibly partly because of lower numbers of specimens.

The distribution of diameter (Di) values (Fig. 9) follows similar trends as for the depth values, inasmuch as lenses possess the lesser diameters with the mode at 12 mm., but significant numbers of specimens of lenses have a diameter of 10 mm. Buttons reveal a marked mode at 14 mm., with significant numbers of specimens having diameters of 10 mm., 12 mm. and of 16 mm. on either side of the mode of the polygon. Round cores again show higher values still, but again also a wide-spread distribution of those values.

Plotting the ratios of depth to diameter, based upon numbers of specimens possessing similar ratios of De to Di (Fig. 10), reveals that the ratio for both buttons and lenses is characteristically 1 : 2, but significant numbers of the button-shaped australites have a ratio of 1·0 : 1·5. The round cores show a similar 1 : 2 trend, but this is by no means as marked as in the button- and lens-shaped types where there are much larger populations.

The scatter diagram depicting depth and diameter values for individual specimens of the round forms of australites from Port Campbell typically reveals a general and steady increase of diameter values with increase in depth values (Fig. 11). Most of the values are concentrated in the region of the 1 : 2 gradient line. Here again, as noted also for Fig. 7, there is observed a number of examples having the same depth value but a range in diameter values, and vice versa, but this does not radically affect the general trend of increasing diameter with increasing depth. Specimens with the same depth but different diameters reflect an origin from primary forms of originally different diameters, ablated to different degrees to yield ultimate secondary shapes of similar depth. Specimens with the same diameters but different depths point to an origin from primary forms of similar original size, ablated to different degrees to yield ultimate secondary shapes of different depth.

Such variations in the ablation process during earthward atmospheric flight seem to indicate somewhat varying speeds of transit and/or possibly different lines of flight through the earth's atmosphere. Faster-moving specimens, although taking slightly less time to traverse the thickness of the earth's atmosphere, may have suffered deeper ablation effects. Somewhat slower-moving specimens may have had longer lines of flight through the atmosphere, and hence suffered comparable degrees of ablation. Slower-moving specimens traversing shorter earthward paths would be probably less ablated than faster-moving specimens traversing similar shorter earthward paths.

The relationships of the intercepts OM and ON cut off by the intersection of the radical line on the depth line (cf. Fig. 3) for the round forms of the Port Campbell australites are shown in Figs. 12 to 15. Most of the OM values for buttons and lenses fall on the 3 mm. co-ordinate (Fig. 12), with significant numbers having a value of 4 mm., while most of the ON values for buttons (Fig. 13) fall in the 3 mm. to 6 mm. range, those for lenses occurring at a prominent mode of
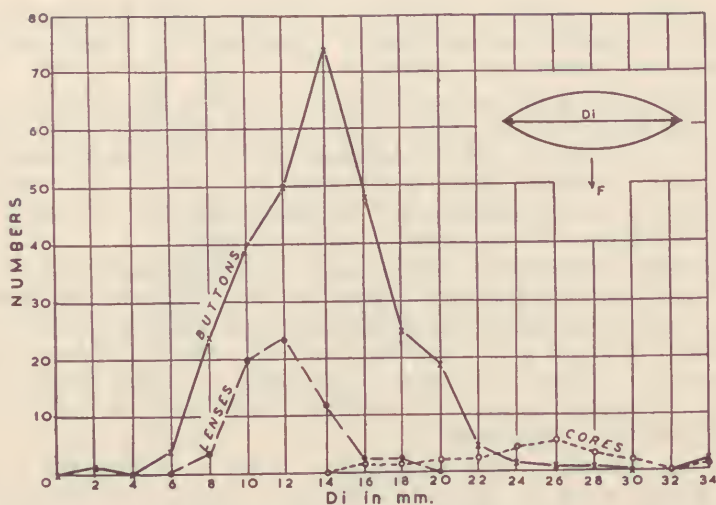
FIG. 9.—Frequency polygon showing Diameter-Numbers relationships for round forms of the Port Campbell australites.
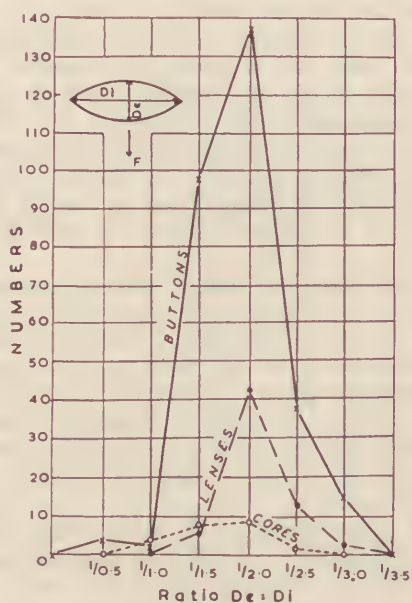


FIG. 10.—Frequency polygon showing De : Di - Numbers relationships for round forms of the Port Campbell australites.

3 mm. Round cores show a tendency towards modes of 9 mm. for OM values (Fig. 12) and of 6 mm. for ON values (Fig. 13).

Relationships between the ratio OM : ON and numbers possessing the same ratio value among the round forms of the Port Campbell australites are shown in Fig. 14. Here the button-shaped forms provide a mode at the 1 : 1·5 ratio, but almost similar numbers yield a 1 : 1 ratio, thus indicating that the button-shaped australites are largely lenticular in cross sectional aspect, but by no means all have the perfect symmetry indicated in cross sectional aspect by the lens-shaped types,
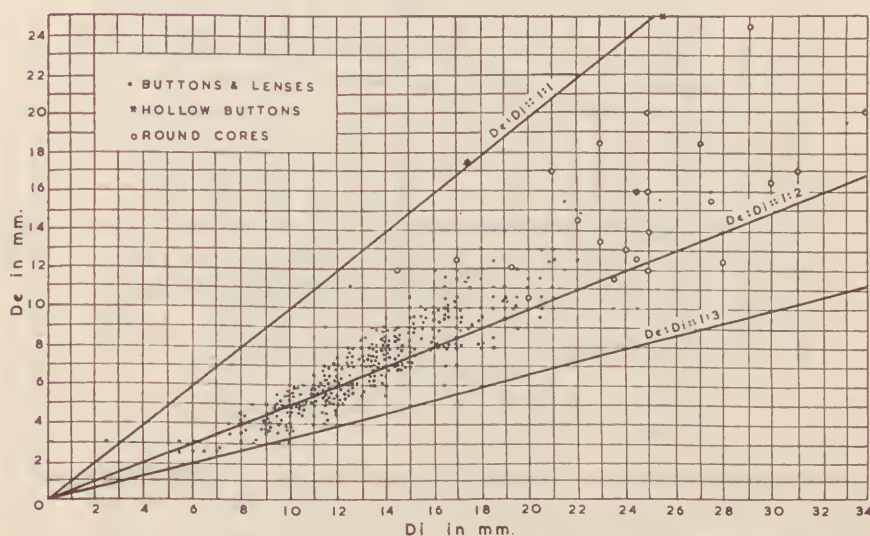


Fig. 11.—Scatter diagram showing Depth (De)-Diameter (Di) relationships for each individual round form of the Port Campbell australites. (Round discs and round bowls excluded.)

which provide a prominent mode at unit ratio. In these forms with a 1 : 1 ratio it is evident that the front and back poles are equally spaced from the mid-point of the specimen, and the plane containing the mid-point (i.e. the horizontal plane containing K, O and L in Fig. 3) is thus virtually a plane of symmetry. In round cores, on the other hand, most examples have OM : ON ratios of 1 : 0·5, which means that in the majority of such specimens the back pole is spaced closer to the horizontal plane than is the front pole, and hence the horizontal plane containing K, O and L is not a plane of symmetry.

Fig. 15, illustrating the relationships between values of OM and ON for individual round forms of australites from Port Campbell indicates that there is a general, even if somewhat scattered and rather irregular, increase in OM values with increase in ON values. The greatest number of OM and ON values for buttons and lenses fall between the 1 : 1 and the 2 : 1 gradients of ON : OM in Fig. 15, but the values for round cores are widespread and range from 1·5 : 1 to the 1 : 4·5 gradients.
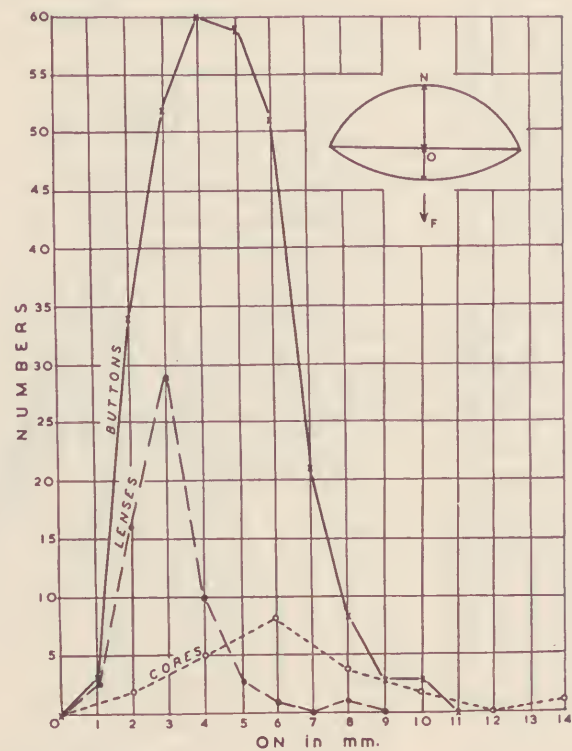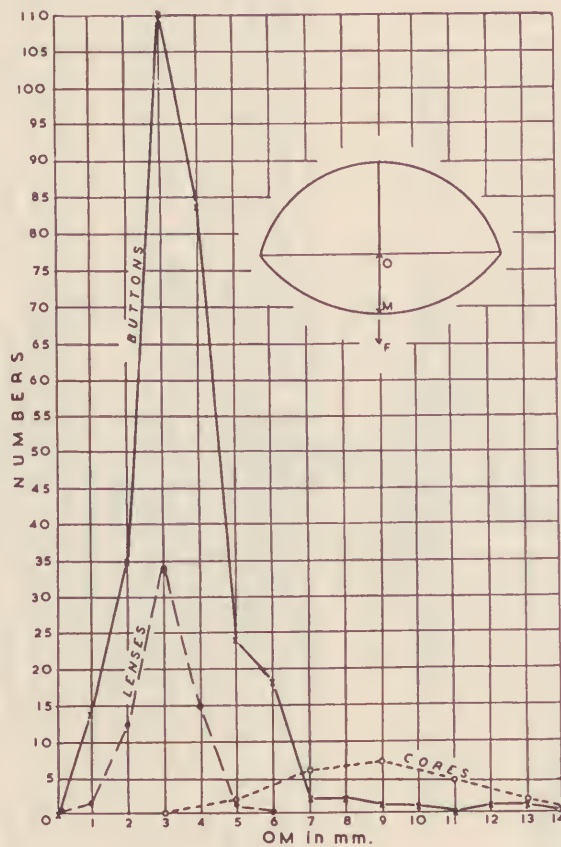
FIGS. 12 and 13.—Frequency polygons showing OM-Numbers and ON-Numbers relationships for round forms of the Port Campbell australites.
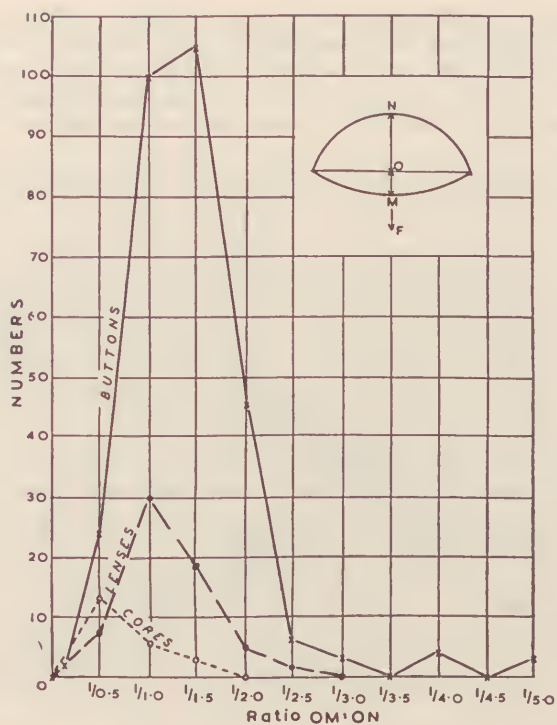
FIG. 14.—Frequency polygons showing OM : ON - Numbers relationships for round forms of the Port Campbell australites.
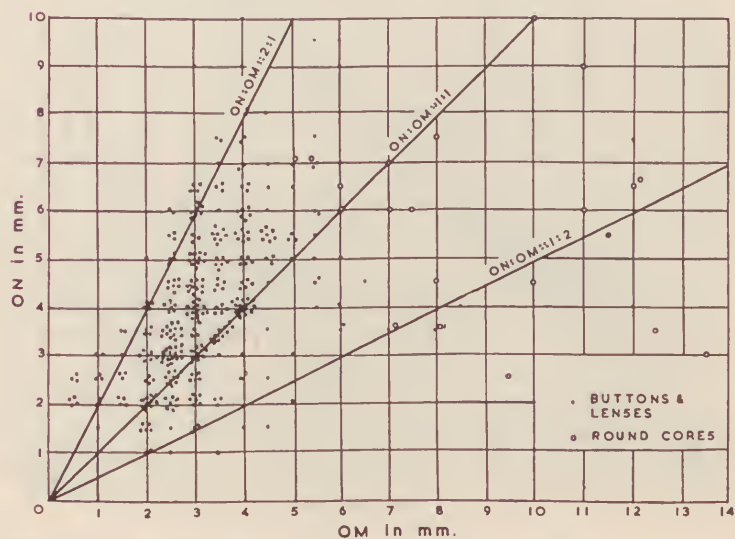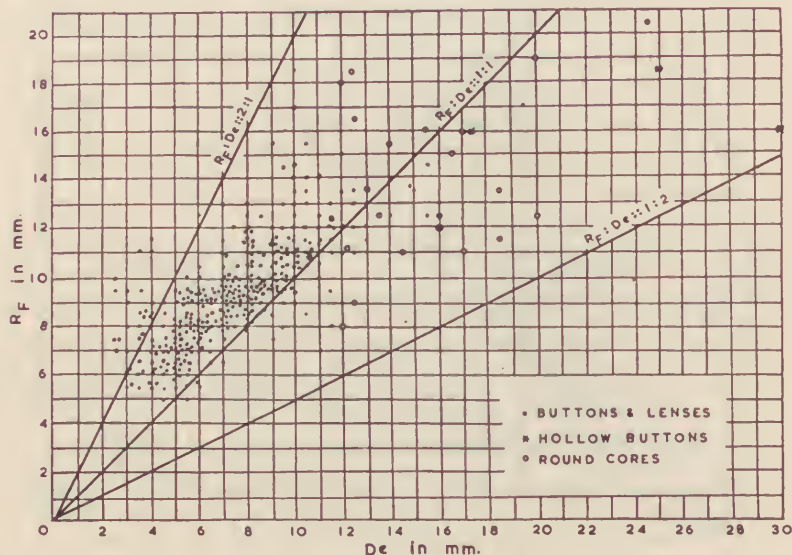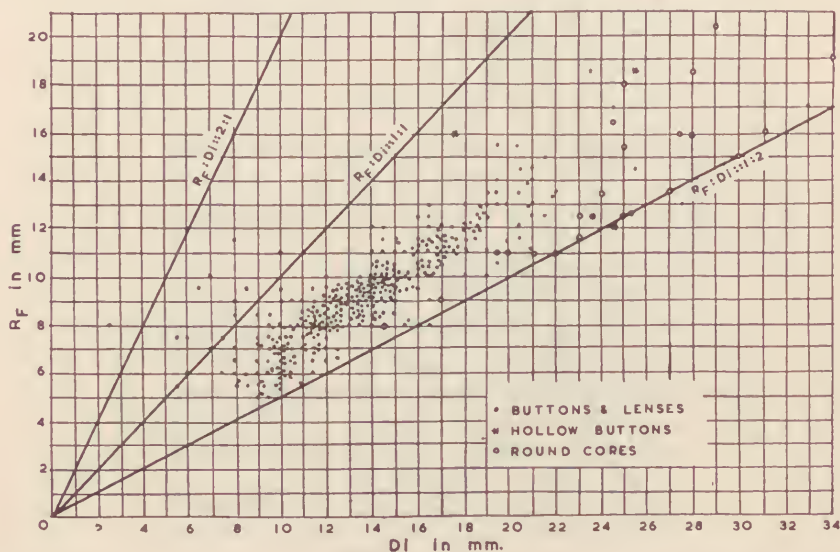


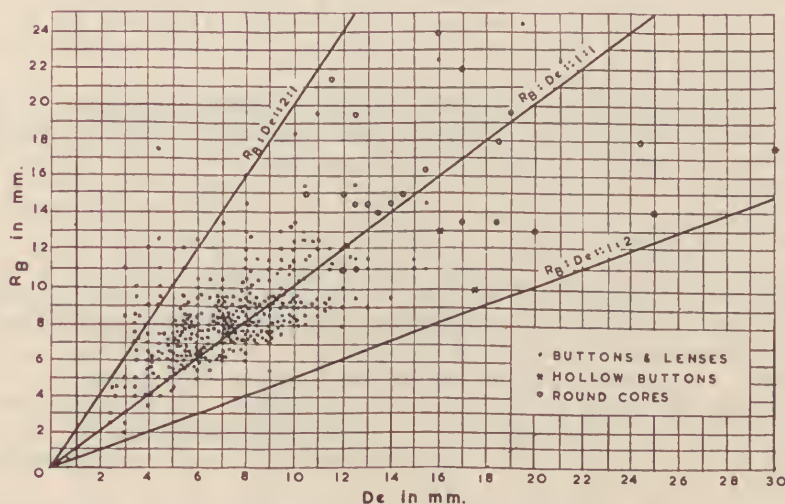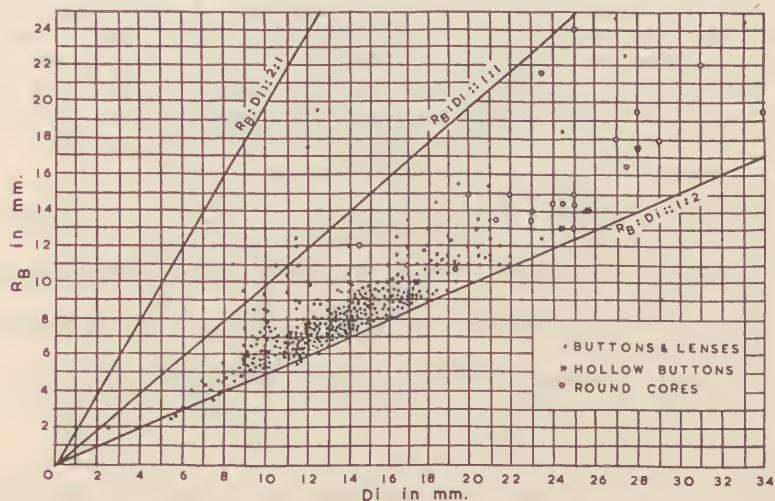FIG. 15.—Scatter diagram showing ON-OM relationships for each individual round form of the Port Campbell australites.

Scatter diagrams for the relationships between each of the following pairs of values, viz., $R_F$ - ON, $R_B$ - ON, $R_F$ - OM, $R_B$ - OM, Di - ON, Di - OM, De : Di - OM : ON, $R_B$ : $R_F$ - De : Di, $R_B$ : $R_F$ - OM : ON, $R_F$ - Di, $R_B$ - Di, $R_F$ - De and $R_B$ - De, all show interesting and somewhat comparable trends, but of these, only $R_F$ - Di, $R_F$ - De, $R_B$ - Di and $R_B$ - De are reproduced herein (Figs. 16 to 19).





Figs. 16 and 17.—Scatter diagrams showing $R_F$-Di and $R_F$-De relationships for individual round forms of the Port Campbell australites.

$R_F$ - Di and $R_F$ - De relationships (Figs. 16 and 17) reveal that the values for $R_F$ are preponderantly less than Di values, but dominantly greater than De values. The general tendency in each comparison is for $R_F$ to increase in value with increases in both Di and De.

In comparisons of the radius of curvature ($R_B$) of the preserved remnant portion of the primary posterior surface (Figs. 18 and 19), it is found that values for $R_B$ are just as preponderantly less than Di values as are the $R_F$ values, but that fewer $R_B$ values are greater than depth values (Fig. 19) compared to the $R_F$ values



Figs. 18 and 19.—Scatter diagrams showing $R_B$-Di and $R_B$-De relationships for individual round forms of the Port Campbell australites.

that are greater than depth values (Fig. 17). In all of the scatter diagrams depicted in Figs. 16 to 19 there is a notable increase in both depth and diameter values with increase in both $R_F$ and $R_B$ values, this trend being best marked in $R_F$ - Di and in $R_B$ - Di relationships.

### Relationships of Series of Forms having one Common Factor

Although the scatter diagrams reveal generally increasing values for one particular factor as values increase for any other selected factor utilized in the above comparisons, there are, nevertheless, certain numbers of specimens which have the same value for one given factor, but the other factors with which this is compared may show quite a considerable range in values. Thus, basing the comparisons fundamentally upon $R_B$ relationships in the first place, since the back surface is more significant in being a representative remnant of the original primary form, it is found that the following trends result from examining a series of randomly selected values:

(i) there can be various Di values for a number of forms possessing the same $R_B$ values;

(ii) there can be various De values for a number of forms possessing the same $R_B$ values;

(iii) there can be various values of $R_B$ for a number of forms possessing the same Di values;

(iv) there can be various $R_B$ values for a number of forms possessing the same De values.

### Treatment 1

In Table 5, where 74 round form specimens are represented, each having the same value (8 mm.) for $R_B$, there is revealed increasing depth as the diameter increases from 9 to 16 mm. In a similar way, it has been found that for a series of 24 round form specimens possessing the same value (10 mm.) for $R_F$, as the diameter varies from 12 to 19 mm., the depth values for these specimens show an increase from 5·5 to 11 mm.

For such an increase in depth with increase in diameter of forms having the same $R_B$ there must also be equivalent variations in the values of $R_F$, and the centres of the coaxal circles circumscribed about the posterior and anterior surfaces respectively must lie at different, but not necessarily progressive, positions on the ON intercept (or its continuation) of Fig. 3. The relationships of these factors for round forms having the same $R_B$ of 8 mm. are shown in Fig. 20.

It can be seen from Fig. 20 that as diameter increases there is a generally regular increase in depth and likewise an increase in $R_F$. Table 5 shows the respective $R_F$ values obtained by construction from the known values of depth and diameter variations for a constant $R_B$.

Averages of the actual $R_F$ measurements in each of the groups $a$ to $h$ agree generally with the values of $R_F$ for each group determined by the constructions depicted in Fig. 20. Projection on to a common diameter line of the various diameters shown in Fig. 20 yields the relationships of cross sections illustrated in Fig. 21.

Such a series of progressively smaller end shapes as those depicted in Figs. 20 and 21 point to an origin from the regular differential ablation of original glassy spheres of similar size. As ablation processes rapidly proceed during high-speed

earthward flight, there is a progressive diminution in depth and diameter with loss of melted glass from the forwardly directed surface. At the same time, there is a tendency for the radius of curvature of the secondarily produced anterior surface (i.e. $R_F$) to increase at first, so that earlier formed arcs of curvature are flatter. After passing the equatorial periphery of the original sphere, $R_F$ values mostly tend to decrease until in the smaller forms so produced $R_F$ becomes less than $R_B$. Hence $R_F$ also becomes less than the radius of the original sphere, and so the front surface finally develops a steeper arc of curvature than that of the remnant
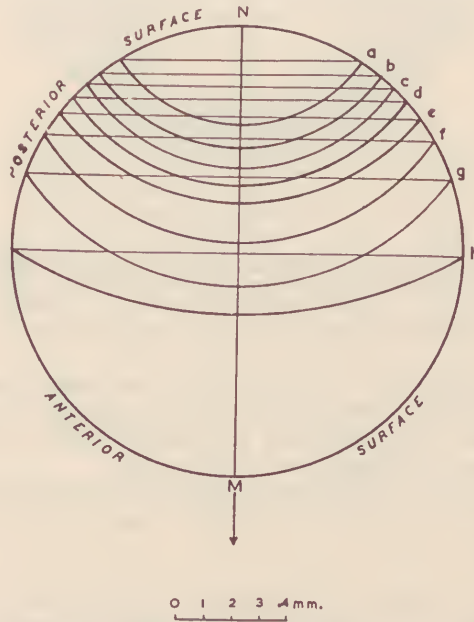


Fig. 20.—Relationships of diameter, depth and $R_F$ for a series of round forms of the Port Campbell australites having the same $R_B$ of 8 mm. (Arrow below M represents direction of propagation through the earth's atmosphere. N = back pole, M = front pole.)

TABLE 5

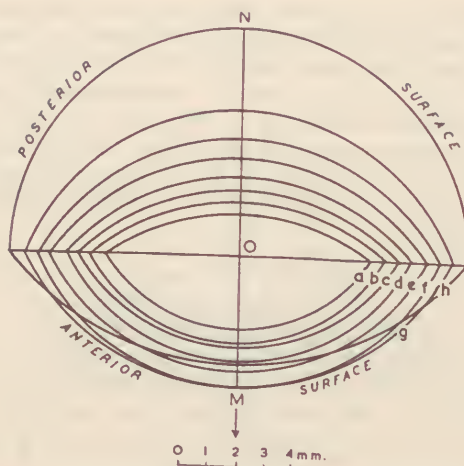| $R_B$ (mm.) | Di (mm.) (average of measurements) | De (mm.) (calculated average) | $R_F$ (mm.) (by construction) | Cross Section on Figs. 20 and 21 | Percentage of group in the series |
|---|---|---|---|---|---|
| 8 | 9 | 3·5 | 5·8 | a | 1·5 |
| 8 | 10 | 4·3 | 6·4 | b | 6·5 |
| 8 | 11 | 5·0 | 8·0 | c | 4·0 |
| 8 | 12 | 5·6 | 8·4 | d | 12·5 |
| 8 | 13 | 6·2 | 9·2 | e | 12·5 |
| 8 | 14 | 7·7 | 9·5 | f | 44·0 |
| 8 | 15 | 9·2 | 9·6 | g | 12·5 |
| 8 | 16 | 10·2 | 15·1 | h | 6·5 |

Fig. 21.—Relationship of cross sectional shapes obtained by projecting the diameters of Fig. 20 on to a common diameter line. (Arrow beneath M indicates direction of earthward trajectory. N = back pole, O = centre of circular horizontal plane containing the diameter line, M = front pole.)

primary posterior surface. For this end to be achieved there must have been increased equatorial ablation and fusion-stripping among the smaller forms. On the other hand, in the earlier stages of the development of a secondary anterior surface, polar ablation must have been dominant.

Similar results to those outlined above have been achieved by utilizing other $R_B$ values than the 8 mm. value employed in Table 5 and in Figs. 20 and 21.

*Treatment 2*

Treatment 2 is the corollary of Treatment 1, and similar results are obtained by considering a series of 70 specimens each having the same $R_B$ of 8 mm., but with depth varying from 4 to 12 mm. By calculation of the average diameters for each group, it is found that diameter values progressively increase in the manner shown by Table 6. Comparable trends also result by selecting groups of specimens with the same $R_F$ value. The relationships for the round forms having the same $R_B$ of 8 mm. are shown in Fig. 22.

TABLE 6

| $R_B$ (mm.) | De (mm.) (average of measurements) | Di (mm.) (calculated average) | $R_F$ (mm.) (by construction) | Cross Section on Fig. 22 | Percentage of group in the series |
|---|---|---|---|---|---|
| 8 | 4 | 9·7 | 6·3 | a | 4 |
| 8 | 5 | 10·7 | 6·4 | b | 11 |
| 8 | 6 | 12·2 | 7·5 | c | 16 |
| 8 | 7 | 13·3 | 8·3 | d | 15 |
| 8 | 8 | 13·7 | 8·0 | e | 24 |
| 8 | 9 | 14·3 | 7·6 | f | 16 |
| 8 | 10 | 15·2 | 8·7 | g | 11 |
| 8 | 11 | 15·5 | 8·5 | h | 1·5 |
| 8 | 12 | 16·0 | 10·0 | i | 1·5 |

Fig. 22 reveals a similar trend to that of Fig. 20. As depth decreases, there is a proportional decrease in diameter and at the same time a general decrease in the $R_F$ values, as shown in Table 6.

Averages of the actual measurements of $R_F$ in each of the groups $a$ to $i$ show fair agreement with the values of $R_F$ (see Table 6) determined by construction from Fig. 22. The origin of these series of secondary end shapes can be explained in terms identical with those already set out in Treatment 1.

Similar trends are again revealed by selecting $R_B$ values other than 8 mm. for identical treatment.
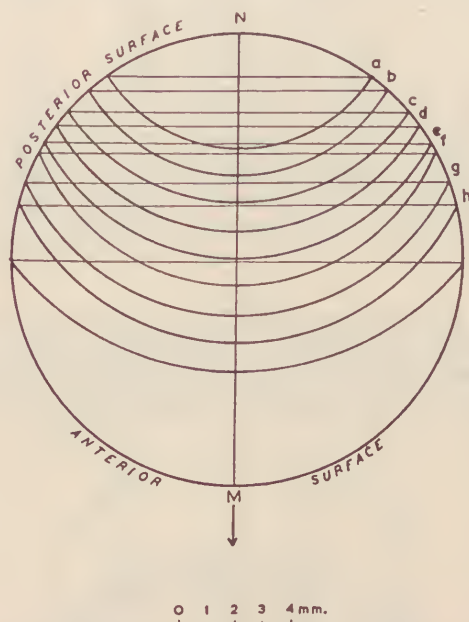


FIG. 22.—Relationship of depth, diameter and $R_F$ for a series of round forms of the Port Campbell australites having the same $R_B$ of 8 mm. (Arrow below M indicates direction of earthward trajectory. N = back pole, M = front pole.)

It is noted from the constructions shown in Figs. 20 to 22 that in each group of specimens the diameter lines are largely situated closer to the back than to the front pole, so that the intercept ON is usually less than the intercept OM for smaller forms, but vice versa for larger forms. The values for the intercepts ON and OM, and the ratio OM : ON for the two series of forms dealt with in Treatment 1 and Treatment 2, are shown in Table 7.

Both series of specimens listed in Table 7 show similar trends, in that for each the ratio OM : ON varies from in the region of $1 : 0.6$ in the secondary shapes of smaller size, to approximately unit ratio for secondary shapes of intermediate size. In the larger specimens, ON has increased to such an extent that the value for this intercept is over twice that of the OM intercept, so that the front pole (M) is thus much closer to the mid-point of the horizontal plane that contains the diameter line (cf. group h, Fig. 21).

TABLE 7

*Showing Intercept Values of the two Series of Forms dealt with in Treatment 1 and in Treatment 2.*

| Group | Treatment 1 (cf. Fig. 20) | | | | Treatment 2 (cf. Fig. 22) | | | |
|---|---|---|---|---|---|---|---|---|
| | Percent | ON (mm.) | OM (mm.) | Ratio OM : ON | Percent | ON (mm.) | OM (mm.) | Ratio OM : ON |
| a | 1·5 | 1·2 | 2·3 | 1 : 0·52 | 4 | 1·5 | 2·5 | 1 : 0·60 |
| b | 6·5 | 1·7 | 2·6 | 1 : 0·65 | 11 | 2·0 | 3·0 | 1 : 0·66 |
| c | 4·0 | 2·1 | 2·9 | 1 : 0·72 | 16 | 2·8 | 3·2 | 1 : 0·88 |
| d | 12·5 | 2·6 | 3·0 | 1 : 0·87 | 15 | 3·3 | 3·7 | 1 : 0·90 |
| e | 12·5 | 3·1 | 3·0 | 1 : 1·03 | 24 | 3·9 | 4·1 | 1 : 0·95 |
| f | 44·0 | 3·9 | 3·7 | 1 : 1·06 | 16 | 4·3 | 4·6 | 1 : 0·94 |
| g | 12·5 | 5·3 | 3·9 | 1 : 1·36 | 11 | 5·3 | 4·7 | 1 : 1·12 |
| h | 6·5 | 8·0 | 2·1 | 1 : 3·81 | 1·5 | 6·1 | 4·8 | 1 : 1·27 |
| i | — | — | — | — | 1·5 | 8·0 | 3·9 | 1 : 2·05 |

### Treatment 3

The relationships of 30 specimens having the same diameter value of 10 mm., but with $R_B$ varying from 5 to 10 mm., show a steady decrease in depth values as the $R_B$ values increase in amount. At the same time $R_F$ values show a decrease followed by an increase. These variations are listed in Table 8. The relationships
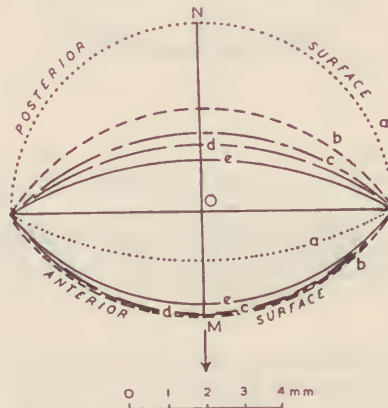


FIG. 23.—Relationships of $R_B$, depth and $R_F$ for a series of round forms of Port Campbell australites having the same diameter value of 10 mm. (Arrow below M represents direction of flight through the earth's atmosphere. N = back pole, O = mid-point of diameter line, M = front pole.)

of these factors are diagrammatically illustrated in Fig. 23. Similarly designated curves on either side of the diameter line in Fig. 23 appertain to the cross-sectional outline of one and the same form group. In this series of forms with the same diameter value it is observed from Fig. 23 that most of the groups (e.g. b, c, d and e) have closely similar radii and arcs of curvature of the secondarily pro-

duced front surfaces, but marked differences for the corresponding back surfaces. Variations in depth cannot be clearly detected from Fig. 23 but are listed in Table 8.

TABLE 8

| Di (mm.) | $R_B$ (mm.) (average of measurements) | De (mm.) (calculated average) | $R_F$ (mm.) (by construction) | Cross Section on Fig. 23 | Percentage of group in the series |
|---|---|---|---|---|---|
| 10 | 5 | 5·5 | 10·5 | a | 10 |
| 10 | 6 | 5·2 | 6·0 | b | 40 |
| 10 | 7 | 4·8 | 5·9 | c | 25 |
| 10 | 8 | 4·5 | 5·8 | d | 18 |
| no sp. | 9 | — | — | — | — |
| 10 | 10 | 3·7 | 6·4 | e | 7 |

Examination of 44 specimens having the same diameter of 12 mm. reveals similar trends to those outlined for the series of specimens having a constant diameter of 10 mm. The trend for $R_B$ increases and depth variations are shown by the values listed in Table 9.

TABLE 9

| Di (mm.) | $R_B$ (mm.) (average of measurements) | De (mm.) (calculated average) | Percentage of group in the series |
|---|---|---|---|
| 12 | 6 | 7·1 | 16 |
| 12 | 7 | 6·2 | 41 |
| 12 | 8 | 5·6 | 20 |
| 12 | 9 | 4·7 | 7 |
| 12 | 10 | 4·5 | 5 |
| 12 | 11 | 5·5 | 2 |
| 12 | 12 | 4·5 | 5 |
| 12 | 13 | 4·5 | 2 |
| 12 | 18 | 4·5 | 2 |

Somewhat comparable relationships are obtained for a series of 20 forms having the same diameter and with $R_F$ values increasing from 5·5 to 8·0 mm. Such a group reveals a decrease of depth from 5·5 to 4·3 mm., but variations in $R_B$ are somewhat irregular in this series.

The secondary shapes examined in Treatment 3 indicate that end forms with the same ultimate diameter may be derived from original spheres ranging in size from 10 to 22 mm. across. This points to different degrees of ablation. During the process there results the following forms among the secondary shapes of australites:

(a) Bilaterally symmetrical, lenticular shapes (in radial section aspect) with similar arcs of curvature for secondarily developed anterior and remnant primary posterior surfaces, such forms possessing an equivalent distribution of glass on either side of the plane containing the radical (= diameter) line.

(b) Forms with $R_F$ markedly greater than $R_B$ and with a greater proportion of australite glass on the back pole side of the plane containing the radical line.

(c) Forms with $R_B$ distinctly greater than $R_F$ and hence a much flatter arc of curvature of the posterior surface, and a greater proportion of australite glass on the front pole side of the plane containing the radical line.

(d) Forms intermediate to those of (a) and (c).

A series such as this indicates that with differential ablation, whereby originally larger primary spheres (or spheroids approximating spheres) have been reduced to secondary end shapes of the same diameter and generally similar size, there has nevertheless been maintenance of stability of position during flight. This is deduced from the fact that each group of the series possesses arcs of curvature suited to constructed coaxal circles, with the centres of the circles being located on the depth line NM or its extension beyond the limits of the forms, and hence collinear.

*Treatment 4*

If a series of 50 forms having the same depth value of 8 mm. is studied, it is found that diameter values increase fairly regularly from 11·5 to 19·5 mm. with increase of $R_B$ values (see Table 10). At the same time, both $R_B$ and $R_F$ values increase regularly, and since the $R_B$ and $R_F$ values are virtually the same as one another in each group of the series, almost perfect lenticular shapes result in radial section aspect, as depicted in Fig. 24.
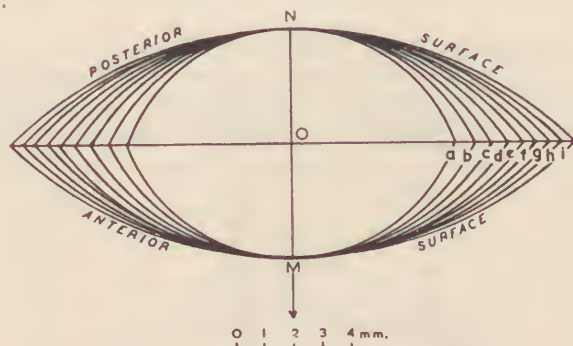


FIG. 24.—Relationships of $R_B$, diameter and $R_F$ for a series of round forms of Port Campbell australites having the same depth value of 8 mm. (Arrow below M represents direction of propagation through the earth's atmosphere. N = back pole, O = mid-point of diameter line, M = front pole.)

It can be seen from Fig. 24 that with constant depth for this series of specimens, as diameter increases, both $R_B$ and $R_F$ increase similar amounts, hence both arcs of curvature become flatter in the larger of the secondary shapes. The values showing these increasing trends are listed in Table 10.

A series of forms thus result having (*cf.* Fig. 24) bilateral symmetry as well as radial symmetry. Each group therefore possesses almost perfect lenticular secondary shapes. The diameter, $R_B$ and $R_F$ values regularly increase from group to group in the series. The deduction is that there has been a progressive reduction in size by the ablation of spheres of an original size range of 12 to 28 mm. across. The originally larger spheres, however, have necessarily been subjected to greater amounts of equatorial fusion-stripping and ablation than the originally smaller spheres.

TABLE 10

| De (mm.) | $R_B$ (mm.) (average of measurements) | $R_F$ (mm.) (by construction) | Di (mm.) (calculated average) | Cross Section on Fig. 24 | Percentage of group in the series |
|---|---|---|---|---|---|
| 8 | 6 | 6 | 11·5 | a | 2·0 |
| 8 | 7 | 7 | 12·5 | b | 22·5 |
| 8 | 8 | 8 | 14·0 | c | 32·5 |
| 8 | 9 | 9 | 15·0 | d | 16·5 |
| 8 | 10 | 10 | 16·0 | e | 12·0 |
| 8 | 11 | 11 | 17·0 | f | 6·0 |
| 8 | 12 | 12 | 18·0 | g | 2·0 |
| 8 | 13 | 13 | 18·5 | h | 4·5 |
| 8 | 14 | 14 | 19·5 | i | 2·0 |

### Production of Secondary Button Shape from Primary Sphere

The above illustrations indicate that the secondary button shapes, which are among the most commonly developed types of australites, were evidently derived from either primary spheres or possibly from spheroids little removed from true spheres in shape.

It is believed (Baker, 1955) that all australites are secondary shapes, produced from a few primary glassy forms by a process of ablation-reduction assisted by fusion-stripping, during passage through the earth's atmosphere at ultra-supersonic velocities of originally cold, non-rotating bodies composed of more or less homogeneous material. The development of shock waves in the air ahead of such rapidly moving objects caused temperature and pressure rises requisite for superficial sheet fusion and the operation of drag effects by skin friction. These two processes were most important in sculpturing the forwardly-directed surfaces of the primary forms, and in producing the ultimate secondary shapes possessed by australites as found. Some of the fused glass was lost by ablation or evaporation, some was whipped away at high speed flight by straight-out fusion-stripping effects without necessarily passing into the vapour state. An original sphere and typical secondary, ultimate button shape produced therefrom are depicted in sectional aspect in Fig. 25.

In Fig. 25 the arrow indicates the direction of propagation at ultra-supersonic speeds through the earth's atmosphere. N represents the position of the back pole on the posterior surface, M the front pole on the anterior surface, and O the point of intersection of the depth line (NM) and the diameter line of the secondarily produced button-shaped form. The circle (broken line) constructed about the arc of curvature of the secondarily developed front (anterior) surface coincides with this front surface in the polar regions, and just meets the crests of the inner flow ridges (i.e. the ridges nearer to the polar regions). Towards the equatorial regions of the front surface, however, the arc of curvature of the flange becomes steeper. In many examples this curvature is flatter, and in a few flanged forms the arc of curvature remains concordant with that of a constructed circle, and hence contiguous with the arc of curvature of the anterior surface of the body of the form. The arc of curvature of the remaining portion of the bubble-pitted posterior surface, indicated by a serrated line in Fig. 25, is part of the arc of curvature of a constructed circle corresponding to a section through a sphere. The posterior surface, which is the top surface in Fig. 25, is regarded as an unaltered residual portion of the original primary form (sphere), and hence its radius of curvature provides the original diameter of the primary form.

c

The flow ridges depicted in sectional aspect in Fig. 25, and also in the sketch of the normal flanged button in Fig. 1, are separated by "flow troughs". The circles constructed about the arcs of curvature of anterior surfaces carrying such flow ridges often fit across the tops of these flow ridges, more particularly the ones situated nearest the front polar regions. Added to the observations (Baker, 1955) made on the internal flow patterns in the regions where flow ridges and "flow
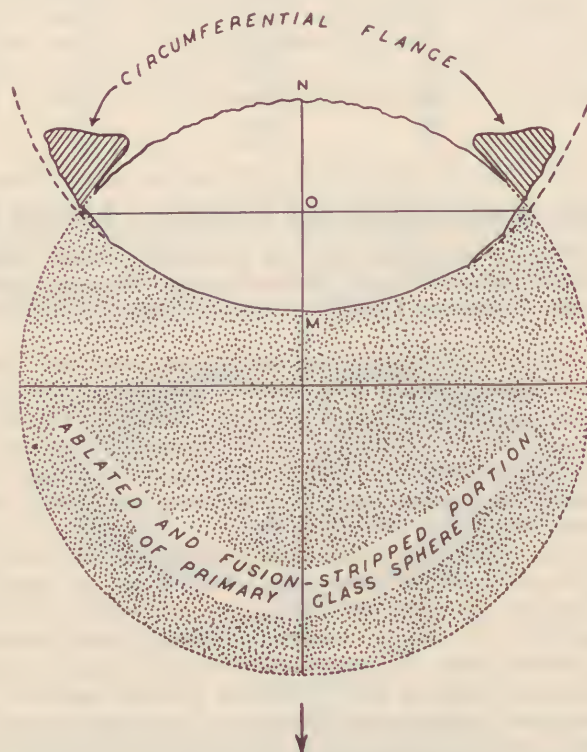


Fig. 25.—Illustrating ablation-reduced and fusion-stripped original sphere of australite glass from which was produced a secondary button-shaped Port Campbell australite having the following dimensions:

| | | | |
|---|---|---|---|
| $R_F$ | = 14·5 mm. | $R_B$ | = 13·5 mm. |
| De | = 10·0 mm. | Di | = 21·0 mm. (ex-flange) |
| OM | = 4·5 mm. | ON | = 5·5 mm. |

troughs" occur, the geometrical position of the ridges indicates that some glass has been removed from the "flow trough" regions, more especially towards the equatorial periphery of each form. The term "flow trough" is thus descriptive of appearance and does not embody an indication of origin. Rather than "waves" of superficially molten glass being generated during movement under pressure and drag from front polar to equatorial regions, it is evident that softened glass has been removed by fusion-stripping from the "flow trough" regions, leaving the slightly projecting ridge-like structures. This applies more particularly to the final stages in the secondary sculpturing processes producing the front surfaces of australites.

Fig. 25 indicates that a considerable proportion of the glass of the original sphere has been lost by ablation and fusion-stripping processes. A small proportion of secondarily melted glass has been accumulated around the periphery of the equatorial regions of the posterior surface, by a process of drag, resulting in the growth of a circumferential flange. Although produced rapidly, as an outcome of the high speed of transit of the object through the earth's atmosphere, it is considered likely that at any particular instant the amount of sheet fusion was never great, and did not exceed 0·01 mm. in thickness before removal occurred under the influence of skin friction and the like. The object was thus not heated throughout, rear portions remaining at low temperatures and low pressures, as testified to by the fact that the rate of heat transference through australite glass is very low (cf. Baker, 1955) and by the fact that there would be generated a region of dead air behind the object moving through a not highly-resistant medium at ultra-supersonic velocity.

There are other examples of button-shaped australites in which the end product indicates that rather less material was ablated and fusion-stripped from the original primary sphere of glass, and some in which rather more material was removed. On the whole, however, the original form was reduced by at least one-half to two-thirds of its bulk before conditions were favourable for the production and preservation in place of the circumferential flange. Subsequent removal of the flange under the effects of increased equatorial fusion-stripping during the near-final stages of atmospheric flight resulted in the production of the non-flanged, lens-shaped types of australites which possess a much smaller number of flow ridges on their forwardly directed surfaces.

## Summarized Curvature-Size Relationships

The various factors concerned with curvature and size which have been determined for the well-preserved round forms of australites discovered in the Port Campbell district are compared on a percentage basis in Table 11.

It is seen from Table 11 that for almost three-quarters of the specimens the radius of curvature of the front surface ($R_F$) is in excess of that of the back surface ($R_B$), so that many of the forms have rather flatter anterior than posterior surfaces. Few are equal in value, resulting in the same arc of curvature for each surface. Approximately one-fifth possess flatter back surfaces (i.e. $R_B > R_F$), and most of the round cores belong to this category. Comparable relationships have been found for the Nirranda district australites (Baker, 1955).

In diameter-depth relationships, the diameter is almost universally greater than the depth, as for the Nirranda australites. As shown by the frequency polygon (Fig. 10) and scatter diagram (Fig. 11), diameter values are typically approximately twice the depth values.

In the relationships of both the depth and the diameter values to the radii of curvature values for anterior ($R_F$) and posterior ($R_B$) surfaces respectively, it is found that diameter is greater than both $R_F$ and $R_B$ for the majority of specimens, more so with $R_B$ than with $R_F$. Specimens with $R_F$ greater than or equal to their respective diameter values consist largely of the very small buttons and the small round discs and round plates. Specimens having $R_B$ equal to or greater than their respective diameter values are very rare among the button-shaped australites, and only one or two occur among the lenses. Depth values are principally less than both $R_F$ and $R_B$ values, but the hollow buttons and most of the round cores have depth values somewhat in excess of $R_F$ values (cf. Fig. 17). Several of the

GEORGE BAKER:

TABLE 11

*Percent Relationships of $R_F$, $R_B$, Di, De, OM and ON for 405 Round Forms of Port Campbell Australites.*

| Factors Compared | Relationship of Factors | Percentage |
|---|---|---|
| $R_F - R_B$ | $R_F > R_B$ | 70·0 |
| | $R_F = R_B$ | 8·0 |
| | $R_F < R_B$ | 22·0 |
| Di — De | Di > De | 99·25 |
| | Di = De | 0·25 |
| | Di < De | 0·50 |
| $R_F$ — Di | $R_F >$ Di | 4·2 |
| | $R_F =$ Di | 1·5 |
| | $R_F <$ Di | 94·3 |
| $R_B$ — Di | $R_B >$ Di | 1·8 |
| | $R_B =$ Di | 0·5 |
| | $R_B <$ Di | 97·7 |
| $R_F$ — De | $R_F >$ De | 84·0 |
| | $R_F =$ De | 4·5 |
| | $R_F <$ De | 11·5 |
| $R_B$ — De | $R_B >$ De | 61·5 |
| | $R_B =$ De | 10·5 |
| | $R_B <$ De | 28·0 |
| OM — ON | OM > ON | 19·5 |
| | OM = ON | 16·0 |
| | OM < ON | 64·5 |
| $R_F$ — OM | $R_F >$ OM | 98·2 |
| | $R_F =$ OM | 0·5 |
| | $R_F <$ OM | 1·3 |
| $R_F$ — ON | $R_F >$ ON | 100·0 |
| | $R_F =$ ON | 0·0 |
| | $R_F <$ ON | 0·0 |
| $R_B$ — OM | $R_B >$ OM | 100·0 |
| | $R_B =$ OM | 0·0 |
| | $R_B <$ OM | 0·0 |
| $R_B$ — ON | $R_B >$ ON | 98·0 |
| | $R_B =$ ON | 0·5 |
| | $R_B <$ ON | 1·5 |

normal size buttons, a few of the lenses and round cores, and one hollow button possess depth values which are greater than $R_B$ values (*cf.* Fig. 19).

Among the relationships between the intercepts OM and ON cut off the depth line by the intersecting radical line (= diameter line), it is found that in approximately two-thirds of the specimens ON exceeds OM, although in many such specimens this excess is small, the difference being up to and little more than 0·5 mm. Specimens with OM in excess of ON are found to be mostly round cores and some buttons.

$R_F$ is invariably greater in value than ON, and $R_B$ invariably greater than OM. In few examples, OM is equal to or greater than $R_F$, as in one hollow button and two round cores. ON is equal to or greater than $R_B$ in two other hollow buttons and one normal button.

## Conclusions

A study of the curvature-size relationships of the round forms of australites from the Port Campbell district in Victoria stresses the marked symmetrical character of the secondary end shapes that have resulted from original spheres by the regular ablation and fusion-stripping at high speeds of propagation through the earth's atmosphere. This almost perfect symmetry shown by virtually all the forms that have not been modified by terrestrial weathering is seldom encountered among the components of the tektite strewnfields in other parts of the world.

The relationships of the arcs of curvature and the radii of curvature of the posterior and anterior surfaces, and the general dependance of the diameter, depth and intercept (OM and ON) values upon variations in radii of curvature, indicate the maintenance of steady lines and positions of flight through the atmosphere. This deduction is supported by the fact that the curvatures of the two surfaces of any one secondary shape are coincident with the arcs of curvature of two coaxal circles, added to which it is found that the foci of such circles are collinear, both lying on the polar axis, which in each form was maintained in line with the direction of propagation through the earth's atmosphere. Although the curvature-size relationships do not, in themselves, rule out the suggestion of the possibility of rotatory motion about the polar axis, other evidence has been accrued (Baker, 1955) which indicates that no rotation occurred during the phase of atmospheric flight, so that the secondary end shapes are not products of rotary motion. Apart from the primary spheres, however, all other primary forms were themselves initially forms of revolution, but were evidently developed as such in an extraterrestrial environment. The development of the secondary end shapes discussed herein is regarded as being consequent upon a secondary phase of superficial front surface heating of the primary glass bodies, which entered the earth's atmosphere as cold objects, at ultra-supersonic speeds (Baker, 1955). Frictional drag and pressure effects in the boundary layers and shocks waves generated at such high velocities of earthward trajectory were responsible for shaping the anterior surfaces and so developing the secondary australite shapes such as are found upon the earth's surface.

## PART II—ELONGATED FORMS

## Introduction

The term "elongated" australites is restricted to forms having one diameter greater than the other, so that such forms have width and length in contrast to the constant diameter of the round forms of australites. Based on Fenner's (1940) classification of australite shapes, the elongated australites include ovals, boats, canoes, dumb-bells, teardrops and elongated cores.

The complete or nearly complete elongated forms of the Port Campbell australites, which are sufficiently well preserved for accurate curvature and size measurements, comprise 166 specimens distributed among the various shape types according to the percentages shown in Table 12 and constituting 29% of the sum total of all well-preserved, complete or nearly complete forms recovered from the Port Campbell district during the past 20 years.

| Group | Shape Type | Number of Specimens | Percentage of total number of forms measured |
|---|---|---|---|
| ELONGATED FORMS | Broad ovals | 52 | 9·1 |
| | Narrow ovals | 22 | 3·9 |
| | Oval plates | 11 | 1·9 |
| | Elongated bowls | 9 | 1·6 |
| | Elongated cores | 6 | 1·1 } 29·1% |
| | Boats | 29 | 5·1 |
| | Canoes | 8 | 1·4 |
| | Dumb-bells | 13 | 2·2 |
| | Teardrops | 16 | 2·8 |
| ROUND FORMS | Buttons, lenses, round cores, etc. | 405 | 70·9% |

### Curvature of Surfaces

The shapes of the elongated australites dealt with in Part II of the study of curvature-size relationships in australites are depicted in sketch form in Fig. 26. The outlines and curvature of the two surfaces, anterior and posterior respectively, were determined in a manner comparable with that already described in Part I. The method of obtaining the radii of curvature, the depth values and the diameter values, and standardizations of the method of measurement follow the technique already outlined in Part I of this study.

ELONGATED FORMS OF AUSTRALITES



OVAL          DUMB-BELL

BOAT          TEARDROP

CANOE

ELONGATE CORE

0    1    2    3
CENTIMETRES
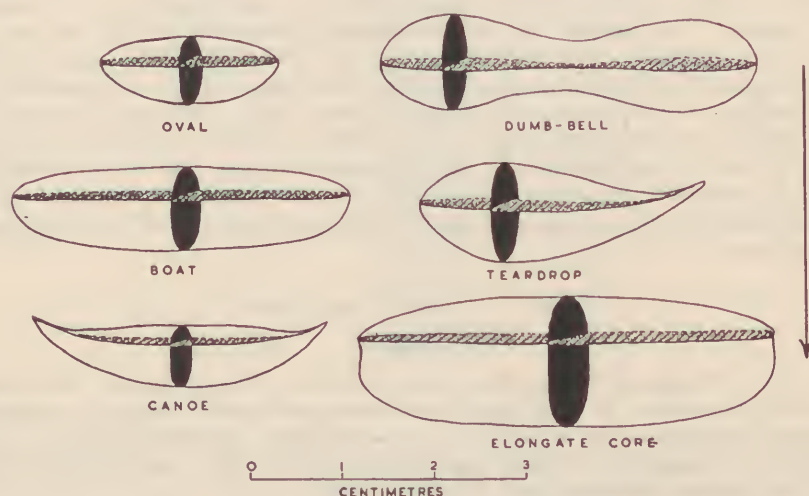
FIG. 26.—Sketch diagrams of the elongated forms of the Port Campbell australites. Posterior surfaces are those at the top of each sketch. (Arrow indicates direction of propagation through the earth's atmosphere.)

As in Part I, the flange dimensions have been omitted from depth, diameter and radius of curvature of front surface measurements, so that the curvature and size

relationships of the body portions of elongated australites could be directly compared in flanged and non-flanged forms alike.

Whereas there are larger numbers in each shape type of the round forms of the Port Campbell australites, this condition is not so satisfactorily realized among the elongated forms. Hence for the purposes of statistical significance the determined values such as depth, diameter, radii of curvature, etc., of each shape type of the elongated forms have been assembled together in kind, in constructing the frequency polygons, although individual values for each member of each particular shape type have been depicted in the scatter diagrams.

The same abbreviations introduced for the terminology of the round forms in Part I of this study are also utilized herein for the elongated australites, except that in place of diameter the terms width (Wi) and length (Le) are employed. In addition, the abbreviations L.S. and T.S. are used in some of the tables to connote measurements made about the two unequal diameters (Wi) and (Le) of the elongated forms. In radius of curvature measurements of front ($R_F$) and back ($R_B$) surfaces, the abbreviation T.S. connotes measurements made in a plane containing the shorter diameter (Wi) and the depth (De) and thus normal to the longer diameter. L.S. connotes measurements made in a plane containing the longer diameter (Le) and the depth (De) and thus normal to the shorter diameter.

Among the less elongated of these australites, one diameter (a) is a little shorter than the other diameter (b) in the equatorial plane of broad oval-shaped forms, with both of these diameters (or axes) usually longer than the third axis (c) which is contained in the polar plane and represents the depth (or thickness) —see sketch of oval in Fig. 27. Therefore (a) = the width, (b) = the length, and (c) = the depth of elongated australites. The axis (b) is always greater than (a) and (c) except in "aerial-bomb" forms (cf. Fig. 27), where (c) is the longer axis and (a) and (b) are approximately equal. The axis (a) is often greater than, but sometimes approximately equal to (c) in all elongated forms except "aerial-bomb"-shaped forms.

The more elongated australites such as the narrow ovals, the boats, canoes, dumb-bells and teardrops have the axis (b) much longer than axes (a) and (c) (cf. boat in Fig. 27), usually in the proportion of 2 : 1, but sometimes, although rarely, up to 11 : 1.

Sections through (or silhouettes of) elongated forms such as ovals, boats and canoes, taken normal to the longer diameter (and thus containing the (a) and (c) axes), and sections through the bulbous portions of dumb-bells and teardrops, possess the same general characteristics as the radial sections taken through the back and front poles of the round forms of australites dealt with in Part I of this study. Like them, similar relationships occur between the arcs and radii of curvature of the front ($R_F$) and back ($R_B$) surfaces respectively. Thus they indicate that the posterior surface is most likely a residual portion of the original primary surface, while the anterior surface is again a secondarily developed surface. Cross sections (i.e. normal to the long diameter) of the original primary shapes were more or less circular, as for the primary shapes of the round forms of australites. Since the elongated forms have this type of cross section, and in addition a longer diameter, it seems probable that all the primary shapes of the elongated australites were originally prolate or oblate spheroids of revolution, some of which became modified at their birthplace, to provide dumb-bell- and teardrop-shaped forms. For the majority of the elongated australites, the longer diameter is normal to the direction of propagation through the earth's atmosphere, and it is usually the axis (c), corresponding to the depth line which is in line with the direction of

earthward flight. Only in the rare "aerial-bombs" which retain a circular cross section normal to the longer (c) axis does the longer axis appear to have been arranged along the line of propagation (*cf.* Fig. 27).

Sections represented by planes containing the longer diameter (b-axis) and the depth (c-axis) reveal that the arcs of curvature along the (b) axis direction seldom correspond exactly to the circular arcs of curvature such as are provided by radial sections through round forms and by cross sections through elongated forms of the australites. More often they provide arcs of curvature suited to somewhat flattened spheroids. Such curvatures are usually steeper towards equatorial regions of the elongated forms, and often much flatter in the polar regions (*cf.* sketch of boat in Fig. 27).
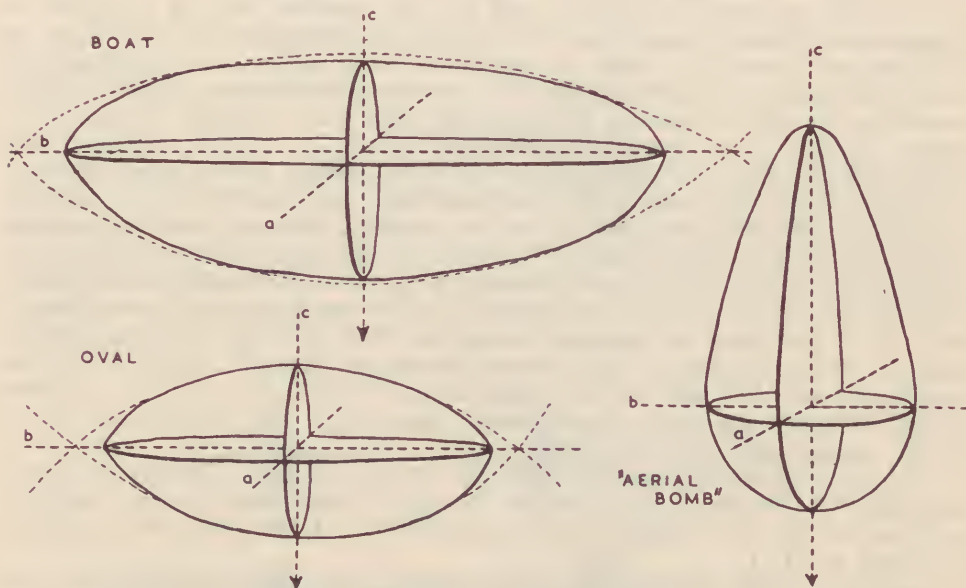


Fig. 27.—Sketches of boat-, oval- and "aerial-bomb"-shaped Port Campbell australites showing axial positions.

In Fig. 27, (a) is the shorter axis representing the width (Wi) in boats and ovals, while (b) is the longer axis representing the length (Le), and (c) the short vertical axis representing the depth (De) or thickness. In the "aerial-bomb" sketch, the (c) axis is the longer axis, while the (a) and (b) axes are approximately of equal length. The broken curved lines represent the arcs of curvature of circles constructed about posterior and anterior surfaces respectively. The arrows indicate the direction of travel of these forms through the earth's atmosphere, and the posterior surface is placed at the top of each sketch.

In some of the oval-shaped Port Campbell australites, particularly the broad ovals in which the longer and shorter diameters are not greatly different, it has been found that $R_F$ for a given form may remain nearly the same in the two positions at right angles—i.e., one position normal to the longer diameter and the other position normal to the shorter diameter. Such forms reveal small differences

in the $R_B$ values and arcs of curvature for the two positions at right angles, i.e. these oval-shaped types are not far removed from the button-shaped australites.

Both the arcs of curvature for the two positions at right angles of both the posterior and the anterior surfaces of broad ovals coincide with portions of the arc of curvature of coaxal circles with collinear centres. But since the arc of curvature of each surface in the two positions at right angles coincide with only one-quarter to one-third of the arcs of curvature of the constructed coaxal circles, it cannot be maintained that each represents portion of the arc of curvature of a sphere. Rather do they seem to indicate derivation from a spheroid of revolution not far removed from the spherical shape. The more elongated forms such as narrow ovals, boats, etc., on the other hand, were no doubt derived from primary spheroids of revolution that were originally more distinctly oblate or even prolate in kind.
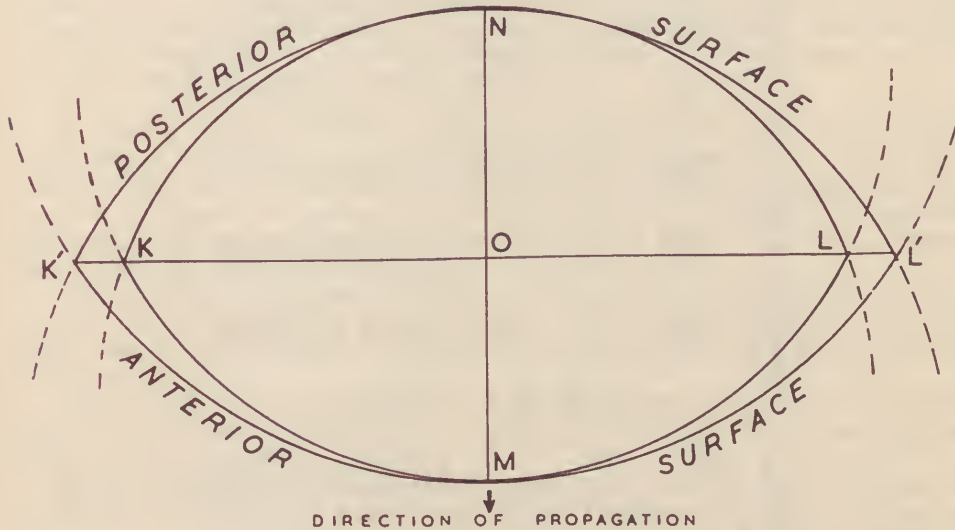


FIG. 28.—Cross sectional aspects of the two positions at right angles of an oval-shaped Port Campbell australite, superimposed on to a common line to illustrate the small differences in the two diameters and in the arcs of curvature of the two surfaces in the two positions.

Inasmuch as the ovals possess two diameters—one longer and one shorter—there are thus potentially two radical lines, if, for the purposes of illustration (Fig. 28), arcs of curvature of posterior and anterior surfaces in the two positions at right angles are tentatively regarded as portions of constructed circles, from which the actual arcs of curvature differ slightly, but nevertheless distinctly, compared with those for button-shaped australites. Thus, in Fig. 28, pairs of coaxal circles have been constructed, with one curve from one pair coinciding with its related curve from the other pair, meeting at the back pole (N), the other two curves from each pair meeting at the front pole (M). In other words, the arcs of curvature across the two diameters for the posterior surface are coincident at the back pole, and those across the two diameters for the anterior surface are coincident at the

TABLE 13

Ranges in Curvature-Size Measurements of 166 Elongated Forms of the Port Campbell Australites.

| Shape Type | Percent of Elongated Forms | Rf (mm.) | | Rn (mm.) | | Ratio Rn:Rf | | Depth (De) (mm.) | Length (Le) (mm.) | Width (Wi) (mm.) | Ratio De:Le | Ratio De:Wi | Ratio Wi:Le | OM (mm.) | ON (mm.) | Ratio OM:ON |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | T.S. | L.S. | T.S. | L.S. | T.S. | L.S. | | | | | | | | | |
| Broad Ovals | 31·5 | 5·0-15·5 | 5·5-22·0 | 3·0-12·0 | 7·0-23·0 | 1:0·76-1:2·0 | 1:0·5-1:1·43 | 2·5-10·0 | 10·0-24·5 | 7·5-19·0 | 1:1·4-1:4·0 | 1:1·1-1:2·7 | 1:1·1-1:1·4 | 1·5-7·5 | 1·0-7·0 | 1:0·33-1:4·0 |
| Narrow Ovals | 13·0 | 5·5-16·0 | 5·5-26·5 | 3·5-15·0 | 5·0-∞ | 1:0·75-1:2·14 | 1:0·46-1:3·60 | 3·5-13·5 | 11·0-36·5 | 7·5-21·5 | 1:2·2-1:4·0 | 1:1·3-1:2·4 | 1:1·5-1:1·9 | 1·0-5·0 | 2·0-9·5 | 1:0·63-1:3·5 |
| Oval Plates | 6·5 | 6·0-∞ | 8·5-∞ | ∞ | 10·5-∞ | — | 1:0·86-∞ | 1·0-2·5 | 9·0-16·5 | 6·0-14·5 | 1:4·0-1:11·0 | 1:3·6-1:9·5 | 1:1·1-1:1·5 | — | — | — |
| Elongated Bowls | 5·5 | (2·5)* | 2·0-6·5 | — | — | — | — | 1·0-4·5 | 7·0-12·0 | 5·0-7·5 | 1:2·0-1:7·7 | 1:1·6-1:6·0 | 1:1·2-1:2·4 | — | — | — |
| Elongated Cores | 3·5 | 10·0-20·0 | 11·5-29·0 | 11·0-22·0 | 14·0-36·5 | 1:0·75-1:0·91 | 1:0·71-1:1·37 | 12·5-16·0 | 22·5-42·5 | 20·0-33·0 | 1:1·5-1:2·7 | 1:1·3-1:2·1 | 1:1·1-1:1·6 | 4·0-10·0 | 5·5-10·0 | 1:0·61-1:2·12 |
| Boats | 17·5 | 4·5-14·0 | 5·5-43·0 | 3·5-12·0 | 22·0-∞ | 1:0·75-1:1·86 | 1:0·41-1:1·0 | 3·0-14·0 | 6·0-39·0 | 7·5-18·5 | 1:2·0-1:5·9 | 1:1·3-1:3·8 | 1:2·0-1:2·9 | 1·0-9·5 | 2·0-8·0 | 1:0·42-1:4·0 |
| Canoes | 5·0 | 3·0-6·5 | (10·5)* | 2·5-8·0 | (26·5)* | 1:0·72-1:2·6 | (1:0·4)* | 2·0-6·0 | 16·5-22·5 | 5·5-10·5 | 1:3·0-1:8·0 | 1:1·7-1:3·8 | 1:1·7-1:3·6 | 0·5-4·5 | 1·0-2·5 | 1:0·5-1:4·5 |
| Dumb-bells | 8·0 | 5·0-15·0 | — | 3·0-15·0 | — | 1:0·63-1:2·14 | — | 4·0-21·0 | 18·0-62·0 | 6·5-24·5 | 1:3·0-1:6·6 | 1:1·0-1:2·1 | 1:2·0-1:4·7 | 1·0-10·5 | 1·0-10·5 | 1:0·42-1:4·0 |
| Teardrops | 9·5 | 4·5-11·0 | — | 3·0-17·5 | — | 1:0·38-1:2·14 | — | 2·5-20·0 | 9·0-43·0 | 5·5-23·5 | 1:1·8-1:6·7 | 1:1·1-1:3·5 | 1:1·1-1:2·4 | 0·5-15·0 | 0·5-5·0 | 1:0·33-1:4·0 |

( )*—1 sp. only

front pole. Where such pairs of curves intersect, at K' and L', and at K and L in Fig. 28, the resultant radical lines K'L' and KL represent the longer and shorter diameters respectively of the oval-shaped form.

## Radii of Curvature, Depth, Width, Length and Intercept Values

The measured radii of curvature for anterior and posterior surfaces in the two positions at right angles indicated by Fig. 28, and also the depth, width and length, as well as the intercept (OM and ON) values, for the elongated forms of the Port Campbell australites are summarised in Tables 13 and 14, on the basis of division into the nine different shape types represented. Ranges in these values are set out in Table 13, and the calculated average values are listed in Table 14. The modes of the values obtained from the construction of the frequency polygons (Figs. 29-31, 33-35, 37, 38, 40 and 42-44) are tabulated in Table 15. For the purposes of the frequency polygons, and hence in Table 15, the various shape types comprising the elongated group of the Port Campbell australites have all been combined, because of low populations among a number of the types and no really large populations among the remaining types.

In Tables 13 and 14 the T.S. and L.S. columns refer to the two positions at right angles along which there are differences of $R_F$ and of $R_B$. In the T.S. direction, the arcs of curvature were found to coincide relatively closely with the arcs of curvature of constructed circles, but in the L.S. direction a moderate percentage only approximately coincide. The infinity sign in Table 13 indicates forms with flat or almost flat surfaces.

Ratios of $R_B$ to $R_F$, of De to Le, of De to Wi, of Wi to Le, and of the intercepts OM to ON are included in Tables 13 and 14. Where pairs of these factors are compared, $R_B$, De, Wi and OM have been retained at unity in the determination of the ratios.

Tables 13 to 15 show the variations in the ratios between selected pairs of these factors, and variations in the values of the measured factors, among the elongated forms of Port Campbell australites.

Radius of curvature values for both front ($R_F$) and back ($R_B$) surfaces are relatively similar for ovals, boats and dumb-bells, somewhat smaller for canoes and teardrops, and markedly increased for the elongated cores. Depth values reveal a considerable range. Length and width values for the broad and narrow ovals show a marked range, and the ratio between these two factors determines their classification; the ratios 1 : 1·1 to 1 : 1·4 represent broad ovals, and the ratios 1 : 1·5 to 1 : 1·9 represent narrow ovals. The narrow ovals are distinguished from the boat-shaped forms, which have a ratio of Wi : Le of from 1 : 2·0 to 1 : 2·9. Lengths of forms in the other shape types vary markedly, with long forms represented among the dumb-bells, teardrops and elongated cores. Variations of the intercepts OM and ON are generally comparable throughout the various types (Table 13), while the average values of these intercepts increase from oval plates and oval bowls, through canoes, teardrops, ovals, boats and dumb-bells, to the elongated cores.

## Frequency Polygons and Scatter Diagrams

The following frequency polygons illustrate the distribution of the values of the various measurements made of the elongated Port Campbell australites without differentiation into the various shape types. This became necessary because of low populations in most of the nine shape types represented and little prospect of

TABLE 14

*Average Values of Curvature-Size Measurements of 166 Elongated Forms of the Port Campbell Australites.*

| Shape Type | Percent of Elongated Forms | $R_F$ (mm.) | | $R_B$ (mm.) | | Ratio $R_B : R_F$ | | Depth (De) (mm.) | Length (Le) (mm.) | Width (Wi) (mm.) | Ratio De : Le | Ratio De : Wi | Ratio Wi : Le | OM (mm.) | ON (mm.) | Ratio OM : ON |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | T.S. | L.S. | T.S. | L.S. | T.S. | L.S. | | | | | | | | | |
| Broad Ovals .. | 31·5 | 8·5 | 11·0 | 8·0 | 12·0 | 1 : 1·15 | 1 : 0·95 | 7·0 | 16·0 | 13·0 | 1 : 2·3 | 1 : 1·9 | 1 : 1·2 | 3·5 | 3·5 | 1 : 1·2 |
| Narrow Ovals .. | 13·0 | 9·0 | 17·5 | 7·5 | 20·0 | 1 : 1·28 | 1 : 1 | 8·0 | 22·0 | 13·0 | 1 : 2·8 | 1 : 1·7 | 1 : 1·7 | 3·0 | 4·5 | 1 : 1·5 |
| Oval Plates | 6·5 | 7·0 | 11·5 | ∞ | 11·0 | — | 1 : 1·38 | 2·0 | 11·5 | 10·5 | 1 : 6·5 | 1 : 5·5 | 1 : 1·3 | 1·25 | 1·25 | 1 : 1 |
| Elongated Bowls .. | 5·5 | (2·5)* | 4·5 | — | — | — | — | 2·5 | 10·0 | 6·0 | 1 : 4·3 | 1 : 2·6 | 1 : 1·6 | 2·0 | 1·5 | 1 : 0·75 |
| Elongated Cores .. | 3·5 | 14·0 | 24·0 | 17·0 | 24·0 | 1 : 0·83 | 1 : 1 | 15·0 | 33·5 | 26·0 | 1 : 2·3 | 1 : 1·7 | 1 : 1·3 | 7·5 | 7·0 | 1 : 1·1 |
| Boats .. | 17·5 | 8·0 | 28·0 | 7·0 | 37·5 | 1 : 1·21 | 1 : 0·65 | 7·5 | 26·5 | 12·5 | 1 : 3·5 | 1 : 1·8 | 1 : 2·2 | 3·5 | 4·5 | 1 : 1·5 |
| Canoes .. | 5·0 | 5·0 | — | 6·0 | — | 1 : 1·22 | — | 4·0 | 19·0 | 8·0 | 1 : 4·5 | 1 : 2·3 | 1 : 2·4 | 2·5 | 1·5 | 1 : 1·74 |
| Dumb-bells | 8·0 | 8·0 | — | 7·0 | — | 1 : 1·4 | — | 8·5 | 34·0 | 12·0 | 1 : 4·4 | 1 : 1·4 | 1 : 3 | 3·5 | 4·5 | 1 : 2·0 |
| Teardrops | 9·5 | 7·0 | — | 7·5 | — | 1 : 1·15 | — | 4·0 | 19·0 | 8·0 | 1 : 3·9 | 1 : 2·3 | 1 : 1·7 | 3·0 | 2·0 | 1 : 1·3 |

( )*—1 sp. only.

TABLE 15

*Modes of Frequency Polygons for Curvature and Size Measurements of Elongated Forms of Port Campbell Australites*

| Shape Group | $R_F$ (mm.) | $R_B$ (mm.) | Ratio $R_B : R_F$ | Width (Wi) (mm.) | Length (Le) (mm.) | Depth (De) (mm.) | Ratio Wi : Le | Ratio De : Wi | Ratio De : Le | OM (mm.) | ON (mm.) | Ratio OM : ON |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Elongated forms (All shape types grouped together) | 8 | 6 | 1 : 1 | 10 | 12 | 6 | 1 : 1·5 | 1 : 1·5 | 1 : 2·5 | 3 | 4 | 1 : 1 |

sufficient numbers ever being found in an area that has been combed for australites for the past twenty years.

In the scatter diagrams (Figs. 32, 36, 39, 41 and 45 to 49) it has been possible to indicate most of the measured values of the separate shape types constituting the elongated Port Campbell australites, and to indicate the values for seven in most scatter diagrams and eight in a few of the scatter diagrams of the different shape types by utilizing conventional signs. Oval plates and elongated bowls can only be used in the scatter diagrams involving width, depth and length measurements (Figs. 36, 39 and 41) because they are either flat or bowl-like and hence not always amenable to $R_B$ and $R_F$ determinations.

In the preparation of both the frequency polygons and the scatter diagrams involving $R_B$ and $R_F$ values (Figs. 29, 30, 31, 32 and 46 to 49) only the measurements across the width, i.e. across axis (a) in Fig. 27, have been employed, since arcs of curvature determined for this position approximate more closely to the arcs of curvature of constructed circles than do the arcs of curvature determined across the length (i.e. across axis (b) in Fig. 27, sketches of boat and oval).

The values of the measurements of the intercepts OM and ON (Figs. 42, 43, 44 and 45) were determined from similar constructions to those from which the employed $R_B$ and $R_F$ values were determined (cf. columns headed T.S. in Tables 13 to 15).
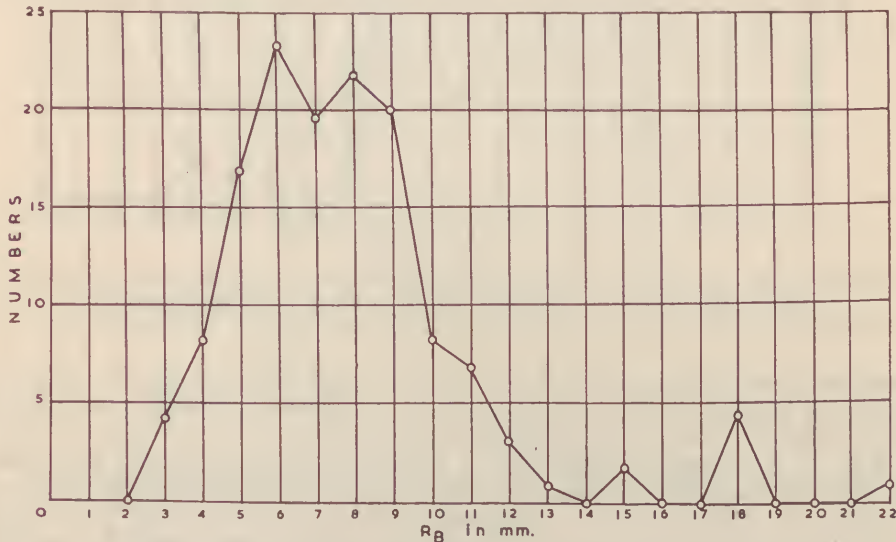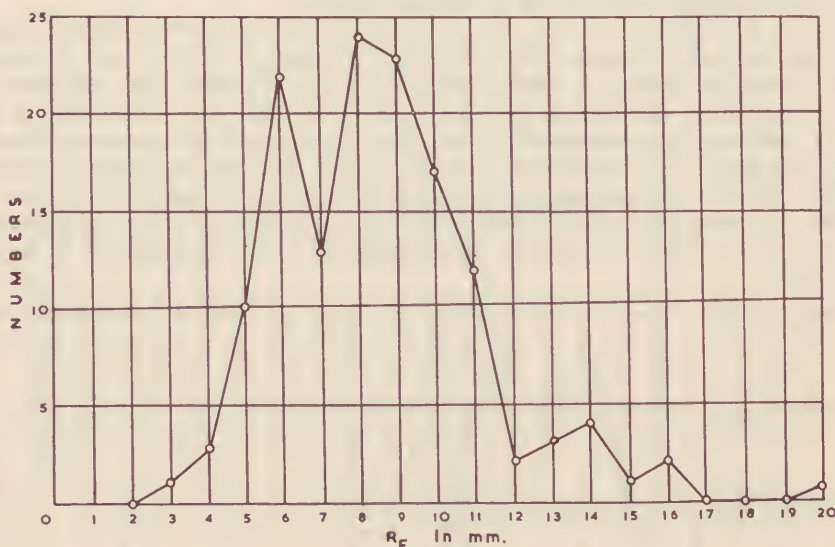


Fig. 29.—Frequency polygon illustrating distribution of radius of curvature of posterior surface ($R_B$) values for elongated shapes of the Port Campbell australites.

The distribution of the $R_B$ values for the elongated Port Campbell australites, shown in Fig. 29, reveals a relatively wide range (2 to 22 mm.), but the greater numbers of specimens possess $R_B$ values between 5 and 9 mm., with a marked mode at 6 mm. and a secondary peak in the polygon at 8 mm. The small trough in the polygon on the 7 mm. co-ordinate, however, has no especial significance.

The $R_F$ values (Fig. 30) show a similar range to $R_B$ values (Fig. 29), and likewise reveal prominent modes at 6 mm. and 8 mm., so that in T.S. sections

through elongated australites the indication is that $R_B$ and $R_F$ values are comparable in amount (*cf.* also Table 14), although there is a somewhat more significant trough in the polygon (Fig. 30) on the 7 mm. co-ordinate.

The ratio of $R_B$ to $R_F$, plotted to the nearest 0·5 (Fig. 31), reveals that a preponderance of forms have a 1 : 1 ratio, while a significant number possess a ratio of 1 : 1·5, thus bearing out the above remarks concerning Figs. 29 and 30. Few specimens have ratios of 1 : 0·5, indicating $R_B$ values twice as great as $R_F$ values. Few specimens have ratios of 1 : 2·0 and 1 : 2·5, indicating $R_F$ values two to two and a half times as great as $R_B$ values. It can be seen from Table 13 that



FIG. 30.—Frequency polygon illustrating distribution of radius of curvature of anterior surface ($R_F$) values for elongated shapes of the Port Campell australites.

occasional dumb-bells and teardrops have the lower ratios of 1 : 0·5, and a few broad and narrow ovals, a few canoes and occasional dumb-bells and teardrops have the higher ratios of 1 : 2·0 and 1 : 2·5.

Fig. 32, showing the relationships of individual $R_B$ and $R_F$ values for separate specimens of the different shape types, reveals a trend of increasing $R_F$ values with increasing $R_B$ values, both for the elongated group as a whole and for the component shape types constituting the elongated group of Port Campbell australites. As noted among the round forms dealt with in Part I of this study, likewise in the elongated group of these australites there occur numbers of specimens with the same $R_B$ value (e.g. 8 mm.) having a range in $R_F$ values (5 to 11·5 mm.), and numbers of specimens with the same $R_F$ values (e.g. 9 mm.) having a range in $R_B$ values (5 to 12 mm.). These, however, do not materially affect the general trends indicated for the group as a whole (*cf.* Fig. 32), and such variations are possibly accounted for in terms of the effects of differential ablation of (i) primary forms of originally similar size on the one hand, and (ii) primary forms of originally different size on the other hand. In other words, similar forms may be differently ablated to result in different arcs of curvature of the anterior surface,
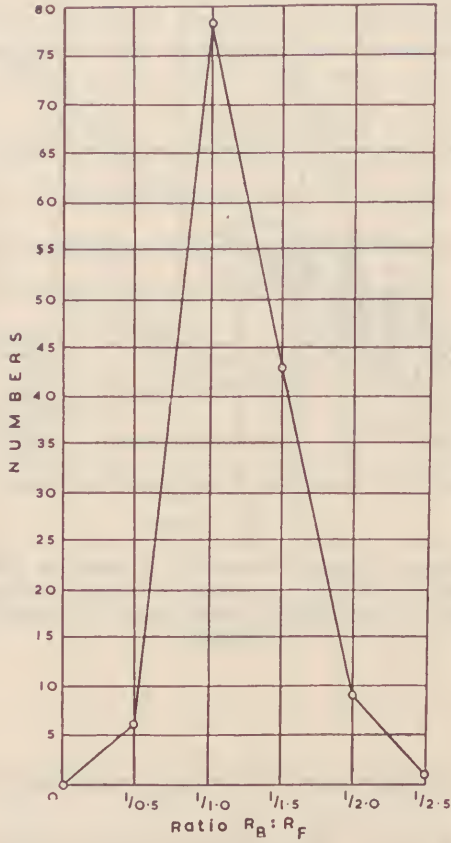
FIG. 31.—Frequency polygon illustrating distribution of $R_B : R_F$ ratios for elongated shapes of the Port Campbell australites.

while by the same process similar arcs of curvature can result for anterior surfaces on end shapes derived from different size primary forms.

The depth values plotted in Fig. 33, although showing a relatively wide range from 2 to 22 mm., are mainly concentrated between 4 and 10 mm., with a pronounced if not very significant mode at 6 mm. The depth values are therefore closely comparable with values for $R_B$ and $R_F$. Most of the thinner forms (4 mm. and under) of the elongated Port Campbell australites occur in the canoe, teardrop, oval plate and elongated bowl shape types. Those of medium depth (4 to 10 mm.) are found among the oval- and boat-shaped types. The thicker forms comprise the elongate cores and one or two of each of the boat-, dumb-bell- and teardrop-shaped elongated australites.

The width values of the elongated australites, shown in Fig. 34, reveal a considerable range from 6 to 32 mm., but with most (92%) in the 6 to 18 mm. width range, where there is a marked mode at 10 mm. and a slight shortage of specimens of 14 mm. width.
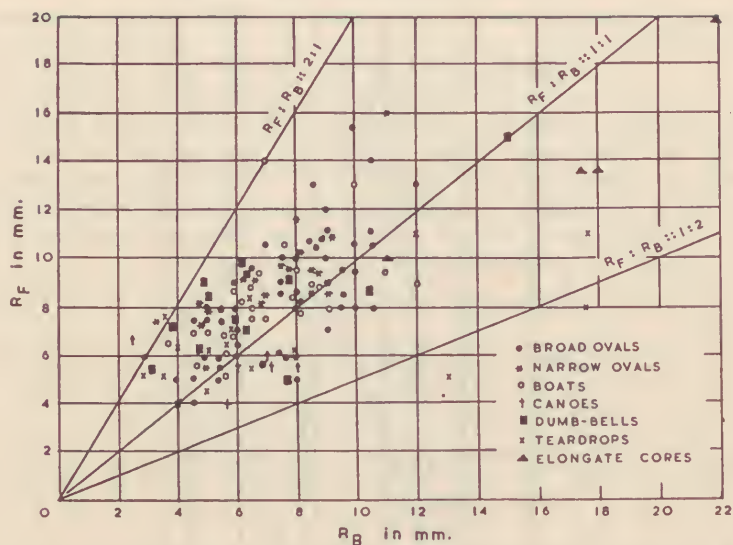
Fig. 32.—Scatter diagram showing relationship of radius of curvature of posterior surface ($R_B$) values to radius of curvature of anterior surface ($R_F$) values for individual specimens of the different shape types of elongated Port Campbell australites.
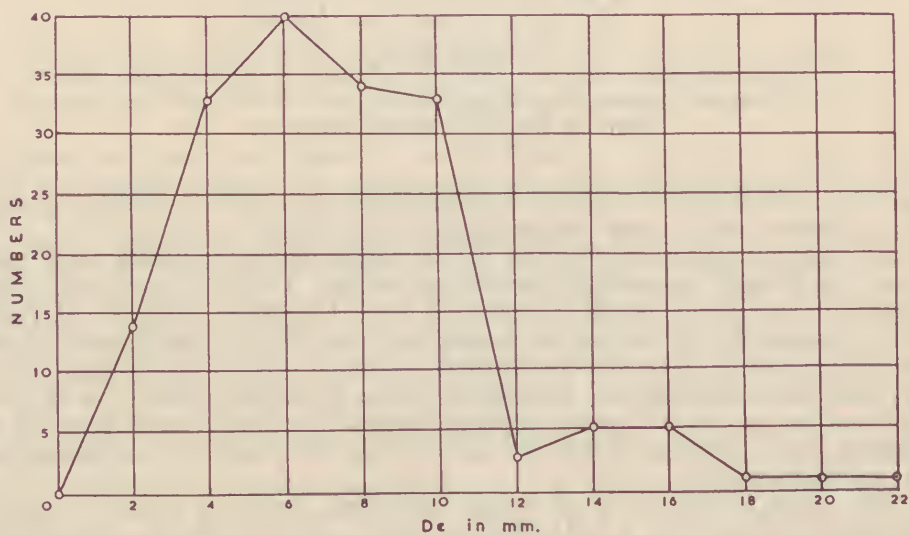


Fig. 33.—Frequency polygon illustrating distribution of depth (De) values for elongated forms of the Port Campbell australites.

Reference to Tables 13 and 14 reveals that the widest forms occur among the elongated cores, and the narrowest among the elongated bowls, canoes and tear-drops. The bulbous portions of one or two of each of the dumb-bells and teardrops, however, possess relatively great width values, being much larger than average size.

The ratio between depth (De) and width (Wi) of the elongated australites (Fig. 35) brings out the fact that a considerable number (80%) of these forms
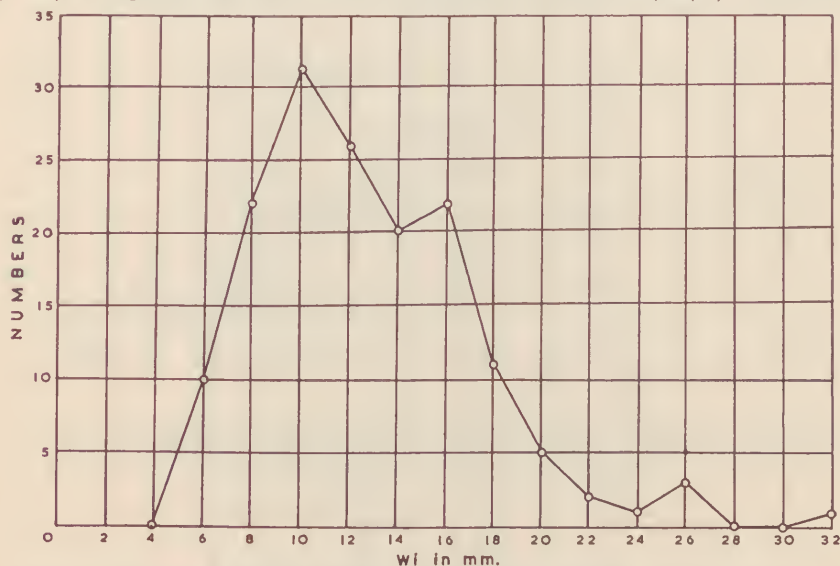


Fig. 34.—Frequency polygon showing distribution of width (Wi) values for elongated forms of the Port Campbell australites.

have width values one and a half to twice as great as their depth values. Only a few (4%) reveal a 1 : 1 ratio, a somewhat larger number (10%) possess a width value 2·5 times as great as that of depth, and a relatively small number reveal ratios of 1 : 3·0, 1 : 3·5 and 1 : 4·0.

The relationships between individual values of depth and width measurements are shown in Fig. 36. Neglecting the relatively thin oval plates and elongated bowls, it can be seen from Fig. 36 that there is a general increase in depth with increase in width. The depth and width values plotted for the dumb-bells and teardrops refer solely to their bulbous portions. Depth and width values tend to increase throughout the elongated australite group from canoes and teardrops, through dumb-bells and narrow ovals, broad ovals and boats, to the thicker and wider elongated cores. Occasional teardrops and dumb-bells occur among the higher values for depth and width. The width values of the oval plates and elongated bowls increase from 5 mm. to nearly 14 mm. for only a narrow range (1 to 4 mm.) in depth (i.e. thickness) values.

The distribution of the length values (Fig. 37) is a relatively widespread one, with a range from 6 to 62 mm. The maximum number (17%) of the total measured have length values of 12 mm., and lesser numbers (each approximately 10%) have lengths of 16 and 20 mm.

D

The ratios between depth (De) and length (Le) provide a relatively uniform distribution, as shown by Fig 38, where it can be seen that the mode of the polygon is on the 1 : 2·5 co-ordinate. Approximately 60% of the specimens have ratios between 1 : 2 and 1 : 3, so that length values are thus usually two to three times as great as depth values, but may be up to eight times as great. A few are only 1·2 to 1·5 times as great, and these are found among the broad oval shape type.
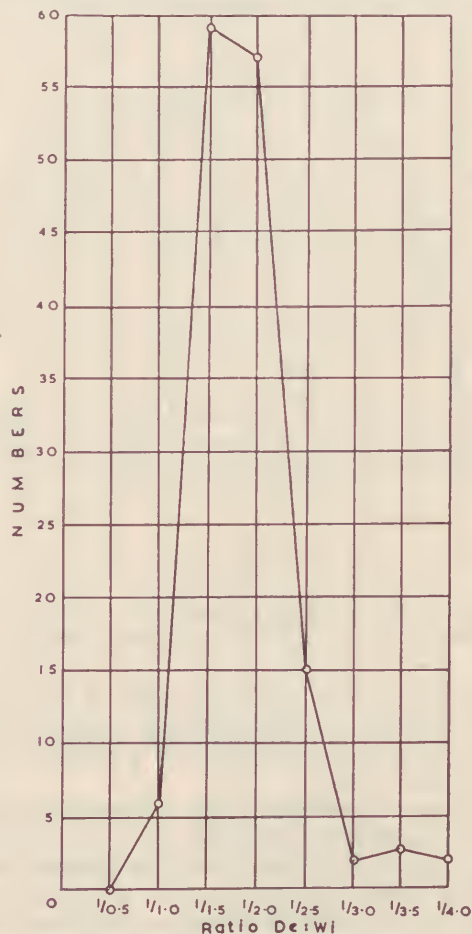


Fig. 35.—Frequency polygon showing Ratio De : Wi-Numbers relationships for elongated shapes of the Port Campbell australites.

The relationships between De and Le values for the individual specimens of these elongated australites reveal a fairly wide scatter (Fig. 39) when the group as a whole is considered. For any particular shape type comprising the elongated group, however, there is observed a marked trend of increasing depth with increasing length, and this trend for each shape type is confined to relatively narrow zones of distribution. This is well shown independently by the broad ovals, by the narrow
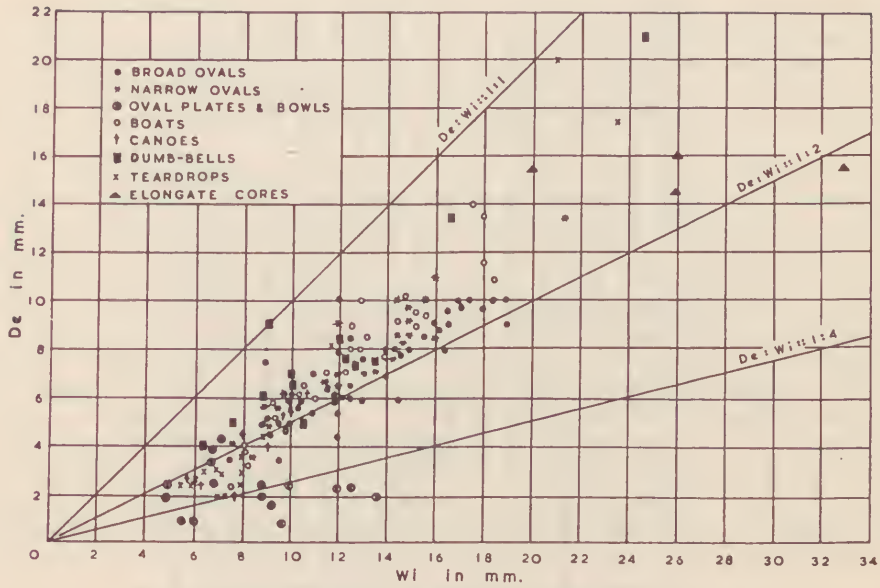
Fig. 36.—Scatter diagram showing relationship of depth (De) and width (Wi) values for individual specimens of the different shape types constituting the group of elongated Port Campbell australites.
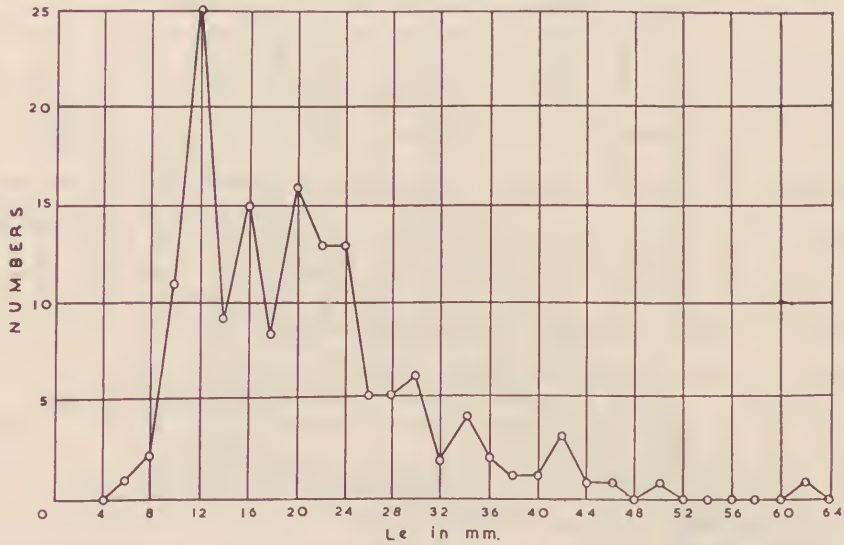


Fig. 37.—Frequency polygon showing distribution of length (Le) values for elongated shapes of the Port Campbell australites.
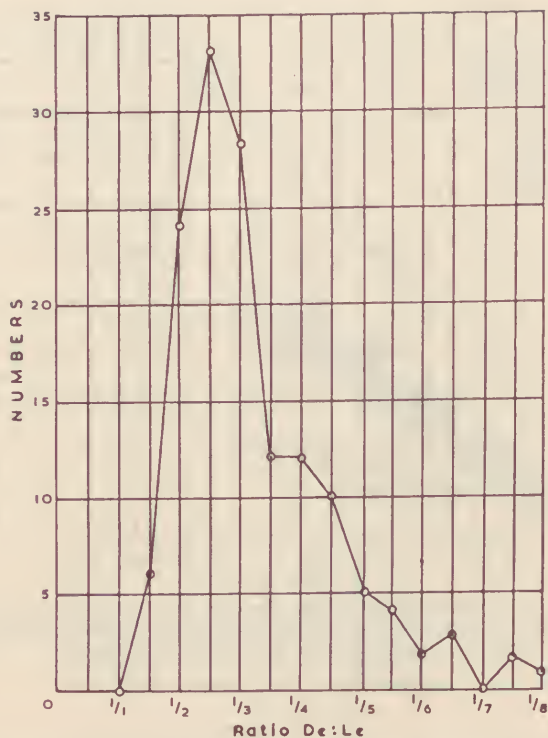
FIG. 38.—Frequency polygon showing Ratio De : Le - Numbers relationships for elongated shapes of the Port Campbell australites.
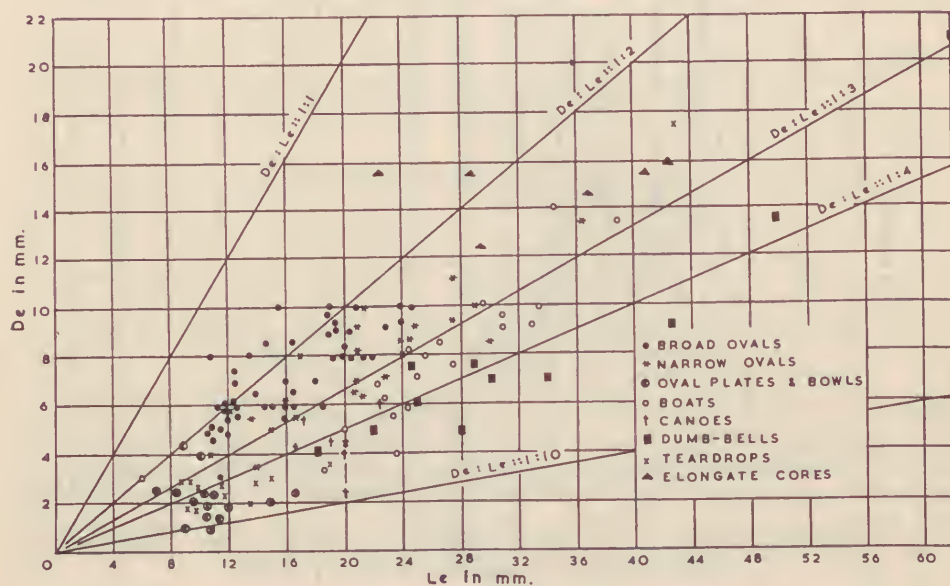


FIG. 39.—Scatter diagram showing relationship of depth (De) and length (Le) values for individual specimens of the different shape types constituting the elongated group of Port Campbell australites.

ovals, and by the boats and dumb-bells in Fig. 39. Among the smaller depth values, however, there is little change to be observed as length increases among the oval plates and elongated bowls. Much the same applies to the teardrops. Among the greater depth values there is also observed a small range of depth (12·5 to 16 mm.) for a considerable range in length values (22 to 43 mm.) of the elongated cores.

The distribution of width-length relationships is indicated by the ratios plotted in Fig. 40. The ratios have been calculated to the nearest 0·5, so that a considerable number (28%) fall on the 1 : 1 co-ordinate, due to many specimens of the broad ovals, together with the oval plates and elongated bowls, possessing length and width values separated by only 1 to 2 mm. It has been shown in an earlier publication (Baker, 1955) that although such differences between width and length values are small, they are nevertheless significant, inasmuch as the differences comprise 10% and over (up to 16%) of the total measurements of these relatively small objects. For this reason, such specimens have been classified with the elongated rather than with the round form group of the Port Campbell australites.

The mode of the frequency polygon (Fig. 40) occurs on the 1 : 1·5 co-ordinate, and this is due to the considerable number of oval-shaped forms which have length and width dimensions which provide ratios indicating length 1·2 to 1·5 times as great as width values. A significant number of specimens providing ratios Wi : Le :: 1 : 2 are composed typically of the boat-shaped forms, accompanied by

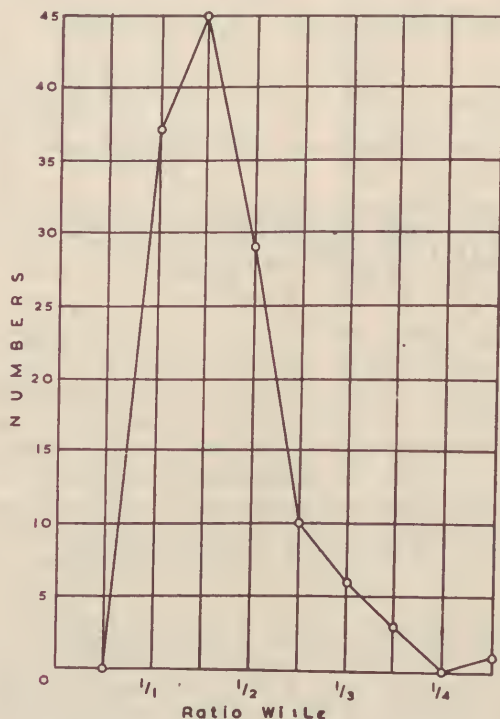

Fig. 40.—Frequency polygon showing Ratio Wi : Le-Numbers relationships for elongated shapes of the Port Campbell australites.

a few teardrops and dumb-bells. Higher ratios of Wi : Le :: 1 : 2·5 and over are found largely among the canoe- and dumb-bell-shaped australites.

The distribution of width and length values of individual elongated Port Campbell australites, shown in Fig. 41, reveals a generally increasing trend of length values with increased width in each of the shape types comprising the elongated group. This trend is rather better pronounced and confined to rather a narrower zone than the depth-length relationships (Fig. 39). The crowding of specimens near the Wi : Le :: 1 : 1 gradient line (Fig. 41) is due to the broad oval and oval plate-shaped types in which length values are not greatly in excess of width values. Only in certain forms, such as the dumb-bells, are the length values as much as three to six times as great as the width values.

In the distribution of the OM intercept values for elongated forms of australites there is a prominent mode (Fig. 42) on the 3 mm. co-ordinate (as likewise found for the round forms discussed in Part I of this study). Thirty per cent of the specimens possess OM values of 3 mm., while significant numbers of specimens (23% and 20% respectively) possess OM values of 2 mm. and 4 mm.

In the distribution of the ON intercept values (Fig. 43) the mode occurs on the 4 mm. co-ordinate, for which value 20% of the specimens are responsible.
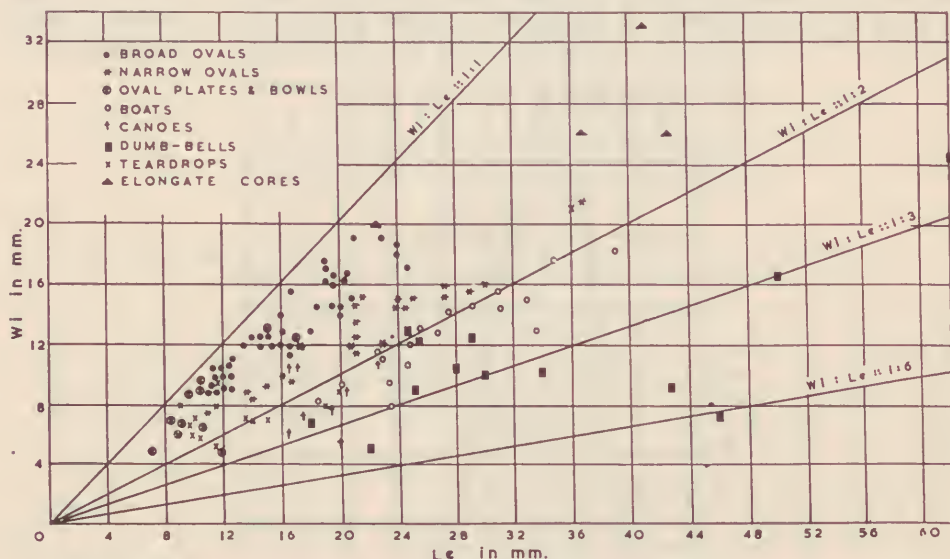


Fig. 41.—Scatter diagram showing relationship of width (Wi) and length (Le) values for individual specimens of the different shape types constituting the group of elongated Port Campbell australites.

There are, however, significant numbers of specimens with ON values of 2, 3 and 5 mm., for which 17%, 18% and 16% of the specimens are responsible.

The ratio OM : ON values show a relatively even distribution (Fig. 44) and therefore only slight skewness of the frequency polygon. Thirty per cent of the forms reveal unit ratio, while 18% have ratios of 1 : 0·5, 24% have ratios of 1 : 1·5, and 14% have ratios of 1 : 2. The remainder range from ratios of 1 : 2·5 to 1 : 4·0.
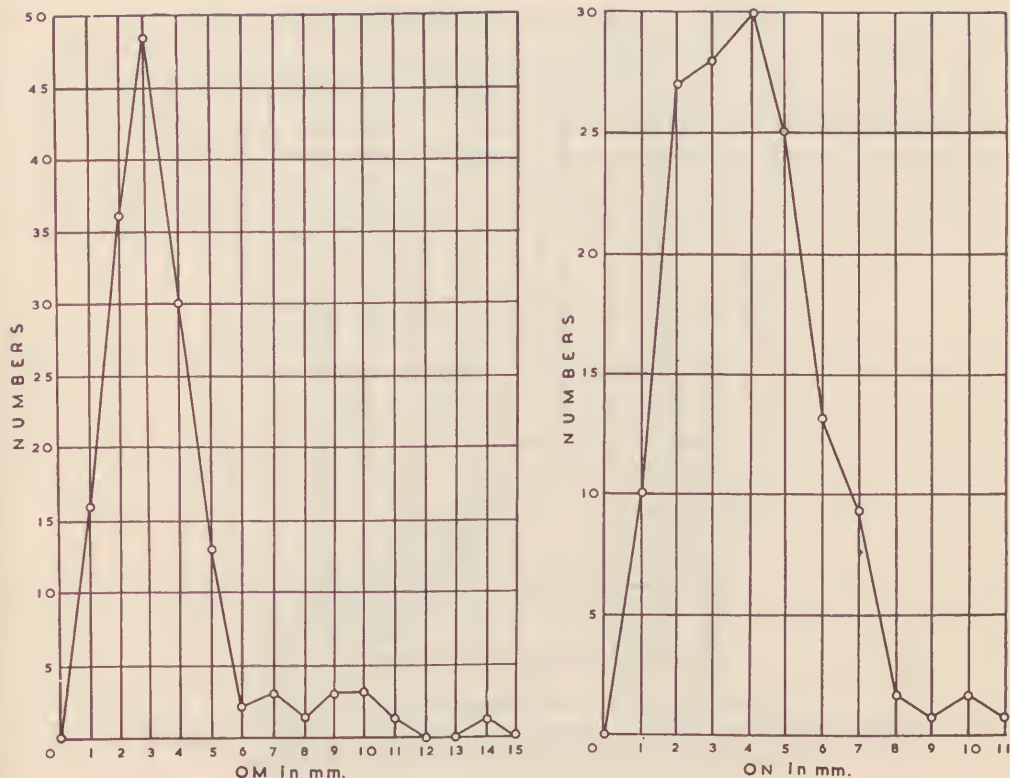
Figs. 42 and 43.—Frequency polygons showing Intercept OM - Numbers and Intercept ON - Numbers relationships for elongated forms of the Port Campbell australites.

The plotted OM and ON values for individual specimens reveal a fairly wide scatter (Fig. 45), but there is nevertheless a general indication that ON values increase with increase in OM values, this trend being best shown among the various shape types by the majority of the dumb-bells and some of the ovals and boats.

In Figs. 46 to 49, showing the relationships of depth and width values to the radii of curvature ($R_B$ and $R_F$) values of the posterior and anterior surfaces of the elongated australites, $R_B$ and $R_F$ have been determined from cross sectional aspects normal to the length. It can be seen that much wider scatters occur for De-$R_B$ and De-$R_F$ (Figs. 46 and 48) than for Wi-$R_B$ and Wi-$R_F$ (Figs. 47 and 49) relationships. In all of these four diagrams there is observed a general tendency for both De and Wi to increase as values of $R_B$ and $R_F$ increase, and this is most pronounced in Wi-$R_B$ and Wi-$R_F$ relationships, where all shape types except the canoes, of which there are relatively small numbers, show regular increases of both factors in each comparison (Figs. 47 and 49), and where the distributions are confined to rather narrow zones.
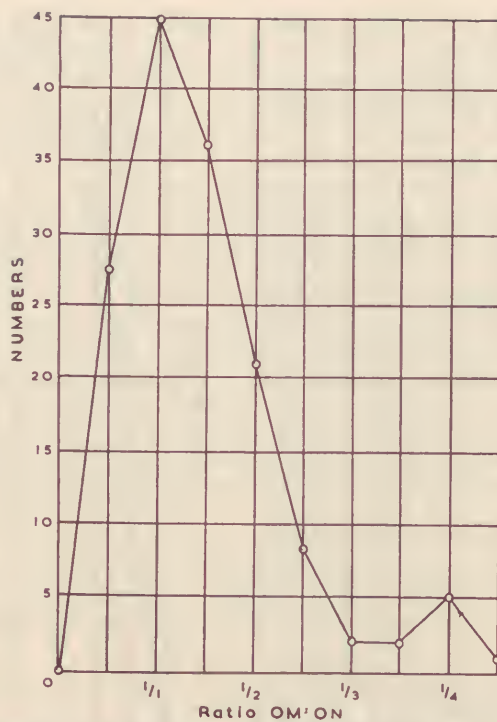
Fig. 44.—Frequency polygon showing Ratio OM : ON - Numbers relationships for elongated shapes of the Port Campbell australites.
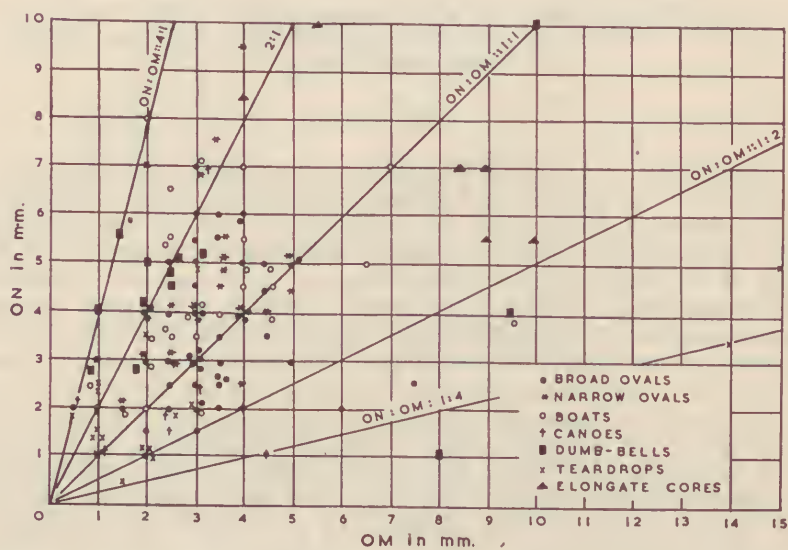


Fig. 45.—Scatter diagram showing relationships of the intercept values, OM and ON, for individual specimens of the different shape types constituting the group of elongated Port Campbell australites.

Irregularities in the relationships between depth values and the $R_B$ and $R_F$ values arise from the fact that the centres of the various arcs of curvature for different specimens are variously located on the depth line (see NM in Fig. 28) or its extension. The arcs of curvature of the elongated australites, when considered solely across their shorter diameter (i.e. width), closely approximate to the arcs of curvature of constructed circles, but not with the degree of perfection observed for the round form group of the Port Campbell australites. Arcs of curvature across the longer diameter (i.e. length) seldom tally with the arcs of curvature of constructed circles.
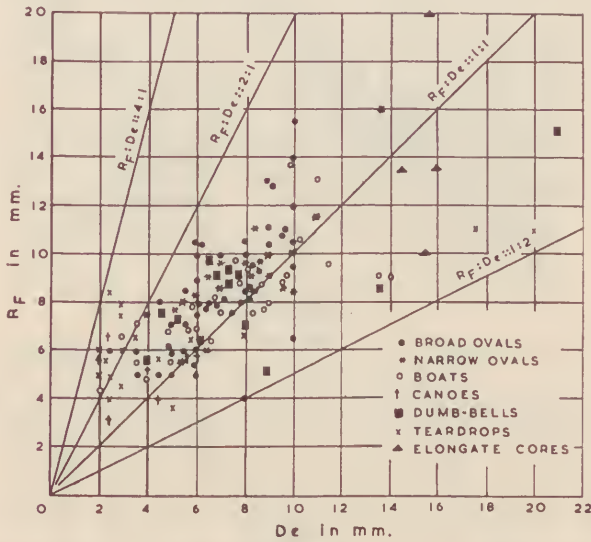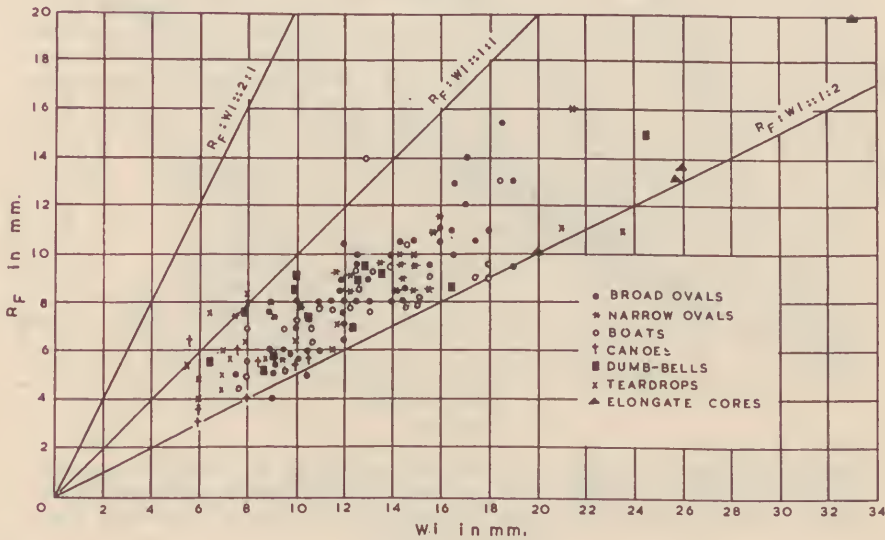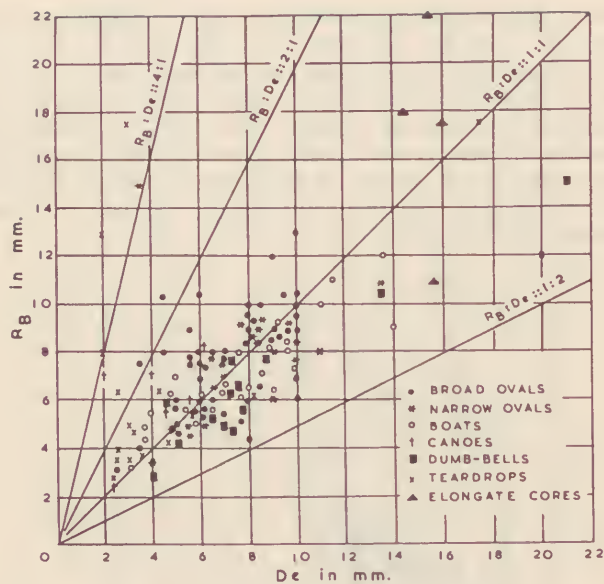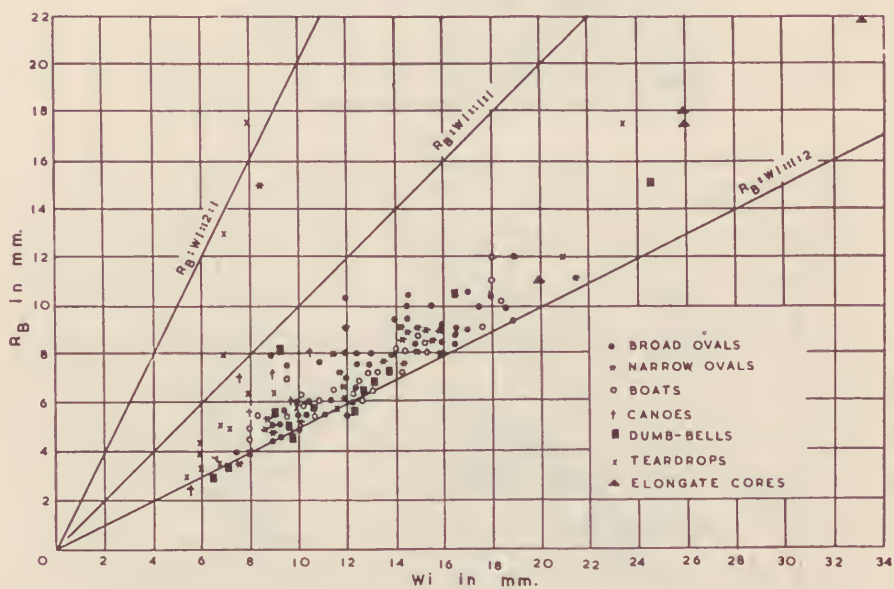


FIG. 46



FIG. 47

Fig. 48



Fig. 49

Figs. 46-49.—Scatter diagrams showing relationships of the radii of curvature ($R_B$ and $R_F$) values to depth (De) and width (Wi) values for individual specimens of the different shape types constituting the group of elongated Port Campbell australites.

## Conclusions

The primary forms from which the secondary shapes of the elongated Port Campbell australites were derived were all originally forms assignable to the limited group of elongated figures of revolution, namely oblate spheroid, prolate spheroid, apioid and dumb-bell. The derivation of the secondary end shapes from ablation and fusion-stripping of primary forms travelling through the earth's atmosphere at ultra-supersonic speeds has already been referred to in Part I of this study.

Frequency polygons and scatter diagrams representing the measurements of the curvature and size of the elongated australites from Port Campbell serve to show the differences between their dimensions and those of the round forms. They also show the general similarity between the arcs and radii of curvature of end-on aspects of the elongated forms and side aspects of the round forms, a trend which is also evident in the smaller population of australites obtained from the Nirranda district (Baker, 1955). Such trends in both the Port Campbell and the Nirranda australites indicate that both have been subjected to comparable amounts of size reduction by similar processes that modified the original primary forms. From a limited number of original shapes were produced limited numbers of modified shape types (i.e. secondary forms) as now found.

## References

BAKER, G., 1955. Nirranda Strewnfield Australites, South-east of Warrnambool, Western Victoria. *Mem. Nat. Mus. of Victoria* (Melb.), No. 20.

FENNER, C., 1940. Australites, Part IV. The John Kennett Collection, with notes on Darwin Glass and Bediasites. *Trans. Roy. Soc. Sth. Australia,* 64: 305-324.